THE HAWAIIAN PLANTERS' RECORD

Vol. XLI THIRD QUARTER 1937 No. 3

A quarterly paper devoted to the sugar interests of Hawaii and issued by the Experiment Station for circulation among the plantations of the Hawaiian Sugar Planters' Association.

In This Issue:

Comparative Irrigation Institutions in Hawaii and in Continental United States and Some Developments Under Them:

Although water law is usually extremely complex and a fruitful field for expensive litigation, the Hawaiian background upon which local conceptions have been built has resulted in a water code for Hawaii which is surprisingly simple and effective. Comparisons with developments in Continental United States emphasize the usefulness of the Hawaiian code under local conditions and once more focus attention upon the magnitude of irrigation developments by the sugar industry.

Scientific Irrigation Management:

We present in this issue a very complete report on scientific irrigation management. It touches on the more important contributions to the subject of plant and water relationships, with special emphasis on the more modern conceptions, particularly those of Briggs and Shantz of the United States Department of Agriculture which are supported by work of Veihmeyer and his associates in California. It is augmented with a discussion of the investigations that have been carried on in Hawaii, especially those that have come from the studies centered at the Waipio substation since 1928, which have formed the basis for establishing certain fundamental relationships for sugar cane growing on Hawaiian soils and which led to the plan to demonstrate that a sound irrigation guidance would come from the recognition and application of the basic principles involved.

After more than two years of actual usage in commercial cane fields at the Waialua Agricultural Company, Ltd., two simple tools—(1) cane growth measurements, and (2) soil moisture determinations—have demonstrated their reliability in guiding the irrigator so that he may secure the maximum cane growth with the greatest economy of water. Thus, much of the former guesswork concerned with irrigation can be eliminated.

The procedures and the results of many studies made in connection with these demonstrations are carefully described, so that the reader may, if he is interested,

duplicate the procedures and make his own interpretation of the results to convince himself of their usefulness.

Finally, the discussion concerned with the administration of plantation water offers some timely suggestions about the equipment and the organization that is needed for this efficient irrigation control, and the way in which the investigational data are used by the field men.

A very complete bibliography of the more pertinent literature is included with the report.

The Value of Irrigation Water as a Factor in Interval Control:

It is well recognized that the value of irrigation water as measured in its ability to produce sugar, varies with time of year and age of crop. Important as this conception is, particularly in time of water shortage, no concrete method of determining the positional value of water on a sugar plantation carrying fields at all ages has ever been worked out.

One possibility of doing this is presented and illustrated by hypothetical cases. How successful the scheme might be can only be determined by trial.

Comparative Irrigation Institutions in Hawaii and in Continental United States and Some Developments Under Them*

By H. A. Wadsworth

Irrigation is a word to conjure with. Perhaps no other word in the English language is so rich in connotations. To the casual reader of romantic western novels "irrigation" immediately suggests prosperous, high-producing areas which come into being almost overnight in the heart of the desert. To the buyer of securities during the early struggles of irrigation finance and again during the expansive period of the nineteen-twenties the word too often means financial loss. The fact that such securities were often purchased under real, but perhaps indirect, encouragement by governmental agencies does not naturally correct the situation. To us in Hawaii, irrigation is a practice by which unpromising agricultural land becomes outstandingly productive, or a system of farming by which at least one of the hazards of agriculture is brought under some measure of control.

A comprehensive consideration of irrigation in all its aspects is neither possible nor desirable. But certain aspects of our local irrigation traditions are in such amazing contrast to those in Continental United States that they deserve more attention than they have received. It is of these contrasts that I would speak tonight, partly because they tend to emphasize the unique position that our irrigation institutions hold among the irrigation communities of the United States, and also because they tend to illustrate the effects of conditions upon the development of legal conceptions.

At the outset it should be recognized that irrigation is a prehistoric art in Hawaii. Both Cook and Vancouver in the accounts of their visits to Hawaii mention the terraces and canals required for the production of taro, while later adventurers, particularly Campbell and Corney, add picturesque details to the description of a practice which was already old. It would be futile and unnecessary to attempt to trace the path by which irrigation came to Hawaii. Such an attempt must await a united opinion by anthropologists as to the origin of the people themselves. But it is safe to assume that whatever their source may have been, the art of irrigation was developed to supplement food production for local consumption and not to increase real estate values nor to increase the flow of produce to remote and already adequately supplied markets.

It is a far cry from the early efforts of the taro grower to the modern achievements of the irrigation engineer in Hawaii, but the chief in prehistoric days, his konohiki and the humble taro grower have all contributed to the legal foundation upon which our modern ventures are built.

The transition from the essentially feudal organization of the early days to our modern practice is complex if detail is demanded but relatively simple in general

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* Address of retiring president, Hawaiian Academy of Science, May 8, 1937.

outline. Early ventures in commercial agriculture by courageous companies, gentle but compelling pressure by mild but persuasive foreigners and the demands of other foreigners not so mild but perhaps even more persuasive conspired to bring into being an amazing series of laws and decrees which have been known as the Mahele or land division. Under the terms of these acts land titles were established. Taro growers might, and did, become owners of the tracts upon which they had labored, chiefs secured unquestioned title to larger holdings while the King and the Kingdom became owners of even greater areas. There is no place here for a detailed account of the labors of the Land Commission which heard claims and did the work necessary for the final granting of title. Let it be sufficient to say that the task was ultimately done. Boundaries were fixed, awards were granted and titles were recorded. In general, present land titles sprung from these awards.

Firmly rooted as the practice of irrigation must have been at the time of the Mahele, it is surprising that no mention of rights to use water was made in the acts themselves nor in the land awards which ultimately resulted from them. It has been tacitly assumed that an award to a certain tract of land carried rights to water as it had been used in the past. Thus, a taro grower receiving a Land Commission Award to a particular kuleana secured, by tacit consent, the right to whatever water was necessary to produce that crop. Water in excess of these claims became the property of the holder of the land award, upon which the water naturally occurred.

Unimportant as this conception may have been during the time of the Mahele, it has formed the turning point of water law in Hawaii since that time. Here, title to water is essentially as real as a land title. It may be leased or sold; it need not be used beneficially nor does lack of use destroy the right. The use of water in a particular stream is not restricted to land adjacent to it.

Active interest in the extension of irrigation facilities for the production of sugar cane began in 1856 and developments have continued at a constantly increasing tempo since that time. By 1898, when annexation by the United States was effected, the first Hamakua ditch on Maui had been completed, the Hanapepe Canal with its intricate design, was delivering water to the fertile slopes of Makaweli and Eleele and two plantations had been organized to grow cane irrigated by water pumped from below ground. It should be noted in passing that in vision, courage and resourcefulness these projects were the equals of anything in operation in the United States at the time, and they were developed under conceptions of water law which were quite unique as far as the extensive production of a crop planned for the world market was concerned.

The peculiarity of local water conceptions seems to have made a great impression upon Theodore Roosevelt in view of his campaign for conservation of natural resources. Shortly after his inauguration he sent James R. Garfield, son of the martyred President, to Hawaii to study the local situation and to recommend such changes as might seem necessary to further the national policy of conservation. The results of this survey have not been widely published but apparently no changes were advised, for none were made.

However, the apparent incompatibility of a local conception with those that had been proven excellent elsewhere provoked further inquiry by students of water law. The fact that the local code worked with the necessity of relatively little irrigation legislation seemed to be its one redeeming feature. Again in 1915 the Governor of

Hawaii apparently became skeptical of the code's soundness as a basis for the rapid extension of irrigation facilities in plantation agriculture, and appointed a committee of three, one of whom is a member of this Academy, to study the local situation and to recommend whatever changes it might see fit toward the end of bringing the local use of irrigation resources into line with common practice in the irrigated West. With considerable wisdom this committee engaged the services of A. E. Chandler, a member of the Public Utilities Commission of California and a water-law attorney of note, to study the situation with its local background and to recommend whatever changes in water administration seemed advisable. Mr. Chandler's report is amazingly brief and recommended no changes. None were made. Here, privately owned water may be considered as real property, title being vested in an individual, or his assigns, and subject to no more governmental scrutiny than any other class of property.

As our local conceptions of water law are the results of early practices, modified as times have changed, so water law in the irrigated West is a composite of early practices, as modified by basic principles of English common law and certain more applicable doctrines of Spanish and Mexican origin. But there the picture is much more complex.

Irrigation came late into the life of the American people. Normal rainfall is adequate for field and orchard crops east of the 100th meridian and seventy-five years were to pass between the beginning of our national life and the significant invasion of this great American Desert, as the region beyond the 100th meridian was known. Conceptions of property rights, some of local origin and some lifted bodily from the Common Law of England, were firmly established before this western migration began. It is only natural that the emigrants carried these conceptions with them. Nor is it surprising that doctrines established in England and found satisfactory in our well-watered eastern seaboard, where the principal duty of streams was to float ships and to operate water wheels, failed to be applicable in the irrigated West. But before this incompatibility had been noted, these doctrines had been incorporated in the laws of many of the Western States.

The situation was still further complicated by the concurrent advent of settlers with backgrounds entirely different from those of the miners and adventurers who had followed the gold trail from the East and Middle West and who had failed to return. These people moving north from Mexico through the Southwest and into California came from an area in which irrigation was and always had been a vital factor in agriculture. To them the waters of their rivers had but little value when allowed to run in their natural channels. To produce wealth, water had to be diverted; it had to be spread over the sun-soaked plains for the production of crops—a procedure which was highly profitable to the diverter but distressing to a potential irrigator along the lower reaches of the stream. For the protection of all concerned such waters were appropriated by ceremonies which have become increasingly formal as waters have become of greater value. Newcomers were made to realize that water could only be available when all prior appropriators had been satisfied, but that prior appropriations might be declared void if no beneficial use was being made of the water diverted.

Such conceptions had proven valuable and adequate in Mexico for many years. Naturally they were carried into the United States and under the aggressive heads

of the newly organized States and Territories of the West, the adjudication of waters in natural streams became a function of the State and Territorial governments. The State became the granter of appropriative rights; the State determined when beneficial use of water had degenerated into non-beneficial use; the State courts ruled in cases involving priorities of use. In spite of the basic application of these conceptions to the use of water in irrigation as compared with the use of flowing water as a source of power, it is evident that they might open the way to almost endless litigation. And indeed they have done so. It is empty comfort to recall that contentions over water rights are as old as man's interest in irrigation. It is said that the English word "rivals" finds its derivation in the Latin "rivus," meaning small stream or ditch. Apparently users of water from the same stream were rivals, in the early use of the word.

Aside from the troublesome details of priority and beneficial use which have been sufficient to flood the court calendars in many Western States, there has always been the possibility of a direct conflict of these conceptions with those of English common law which in some States is the basis of Constitutional rights. The doctrine of riparian rights is dear to the heart of the staunch supporter of English common law. This doctrine, important enough in industrial communities but quite inapplicable in a region in which irrigation is important, holds in general that the natural flows of streams may not be modified by diversions nor by the installation of regulatory dams nor may the waters of the stream be contaminated nor polluted in their passage on their natural course.

Several of the Western States recognized the incompatibility of these two basic conceptions early in their judicial history and rejected the riparian doctrine at the outset, or very early. Others, notably California, clung to it through much costly litigation, the proponents of the riparian principle usually losing ground with each decision.

In 1928 a constitutional amendment was adopted in California which demanded reasonable use from riparian landowners, a condition which apparently runs counter to the doctrine itself. But the necessity of some such limitation is apparent from the history and decision in Herminghaus et al. vs. Southern California Edison Company. In this case the court held that a storage dam, high in the Sierra Nevada Mountains, so controlled the flow of the San Joaquin River that rights of riparian landowners below the dam had been violated. The fact that the riparian landowner involved profited by unregulated stream flow only through the occasional flooding of 18,000 acres of unimproved pasture land seemed sufficient cause, under the doctrine of riparian rights, to delay and financially handicap a great project which had the control of flood waters as one of its ends. It is very doubtful if this decision together with the constitutional amendment which it prompted has quieted the inevitable conflict between such incompatible conceptions.

It is in this atmosphere of conflicting doctrines, of reversed court decisions, costly litigation and judicial delay that American irrigation institutions are founded. The basic law naturally varies in each of the Western States and of course each State makes it own interpretation. Regardless of such variations however, one conception is common to them all, that is that water is the property of the State. Individual use is by permission from the State, such permission being subject to denial or to withdrawal unless certain specified and rigorous conditions are complied with.

By way of contrast one turns again to Hawaii. Here, as has been stated, water is ordinarily considered as real property subject to all privileges of rental, lease or sale. It is a personal asset of recognized worth, as is indicated by the paucity of title transfers.

It is far afield from the purpose of this discussion to debate the social justice behind these two entirely different conceptions of water administration. Both are natural developments of early doctrines which have been modified and strengthened as time and occasion demanded. The point is that our simpler scheme in Hawaii has been surprisingly effective under conditions as they exist here. And in the opinion of at least two of those well qualified to judge, no contingency is conceivable in which the local code will be inadequate.

The methods by which irrigation developments were promoted and financed in Hawaii and in Continental United States are as different as the legal conceptions which permitted them. Here a single, valuable crop with a sure market was to be provided with water. Sugar prices were fairly constant and, except for one or two distressing periods, high enough to encourage ventures into lands too dry to permit cane production without irrigation. Here, until very recently, a sure and open market was available for as much sugar as could be produced. It is true that the market was far from Honolulu in miles but the costs involved were known and the value of the crop at the market was subject to close prediction. Hawaii is once more unique in its background as an irrigated community. Ordinarily considerable trial and error is necessary to determine profitable crops in a newly irrigated area. And too often the natural market for such crops is not only far away in miles but subject to seasonal flooding from other communities with the same ability to produce and with perhaps lower delivery costs. No such difficulties faced the pioneers in Hawaiian irrigation. Here the problem has been to acquire the right to use water, to lead that water to suitable cane land and to devise means of distribution. Such problems are those of the irrigation engineer. They are tangible; they lend themselves to definite solution; they are free from those aspects which so dominate the activities of such agencies as the United States Reclamation Service, perhaps the greatest group of irrigation engineers in the world. Of greatest importance, however, is the fact that in Hawaii the development and use of water followed a need for that water rather than the anticipation of such a need. Here new developments have been financed from the profits of the old; but most significant is the fact that local ventures have not received governmental subsidy in any form. To be contrasted with this practical and extremely utilitarian philosophy is that of the Federal Government and most of the Western States. Due to social implications which have found little manifestation as yet in Hawaii, irrigation in Continental United States has demanded and received encouragement, advice, and financial support by Federal and State agencies in almost unbelievable measure.

Early irrigation enterprises were informal, effective, as far as the actual production of crops was concerned, and ordinarily not particularly costly. But as has been noted elsewhere, new projects had the characteristic of being more expensive than those that had preceded them. Easy diversions invited early effort, and natural dam sites, particularly those demanding only modest investment, were soon utilized by the private and aggressive irrigation pioneer. This phase was soon over, however.

In the meantime the Federal Government had embarked upon a general plan of settling the arid West. By the middle of the 19th century the humid lands of the Mississippi Valley had been superficially occupied and a stream of adventurous souls, looking for land rather than gold, moved westward across the 100th meridian and into an area where irrigation is essential to successful farming.

It is not for us to question the policy of the Federal Government which resulted in the extension of irrigation facilities over this great region. Great tracts of Government land in Western States were ceded to the States with the understanding that the States provide irrigation facilities and resell to actual settlers at the cost of the improvements. A separate bureau in the Department of the Interior was established to provide water for Government land set aside as Reclamation Projects, the thought being that land so improved could be readily sold to new settlers in the districts and that the carefully amortized payments could be made by the settler from profits from the land. It should be said in passing that some of our mightiest engineering achievements have been made under the direction of the Bureau of Reclamation. Even the poor Indian, crowded into reservations particularly in the Southwest, felt the effect of this expansive interest of government in irrigation development. Projects were developed on the reservations with the thought that these wards of the Government might share in the rewards which were to flow from the irrigation in the West.

Without prejudice it must be admitted that the projects have not been entirely successful. It is still true that irrigation is essential for consistent crop production west of the 100th meridian, but it is also true that more is required than a beautifully designed storage dam in the mountains and an intricate system of canals to turn every casual applicant for land into a prosperous and successful farmer. Moreover, there did not seem to be the demand for irrigable land that had been anticipated.

Certain social and economic aspects of the picture had apparently been ignored. Distances to consuming centers were often great in view of the remoteness of some of the projects and transportation costly, particularly during their early struggles. Even more important as a factor in the ultimate success or failure were the limited personal resources of the settlers to whom allotments were granted. Magnificent irrigation structures resulting in bountiful water supplies to arid land do not always spell success in irrigation ventures. It has been said that, on the average, the present holder of one of the allotments is the third in a series. If this be true the successful settler starts, not with bare land, but with a homesite enriched by the capital and efforts of his two predecessors. The steps taken by the late Dr. Elwood Mead to correct this situation and to allow for the inevitable social complications which must develop, is one of the brightest chapters in the history of American reclamation.

Nor had the States remained idle. Legislation providing for the formation of irrigation districts was enacted by each of the Western States. Under such authority unirrigated areas might declare themselves irrigation districts after a specified type of referendum, and by so doing make it possible to bond the district for the purpose of providing irrigation facilities. Being political subdivisions of the States, money for interest and sinking fund was collectible through the ordinary tax collecting machinery of the county. Of greater importance is the fact that such irrigation district bonds acquired a dignity often out of keeping with the real security

behind them. Being bonds of political subdivisions of States they usually became legal investments for savings banks. Once more we note the fine touch of governmental subsidy of irrigation ventures. The fact that in this case the subsidy lies only in the extension of governmental credit does not make it any less real. One should be quick to note the safeguards established by the States in this regard. Every proposed district needed the approval of the State engineer before its formation was permitted. And in many cases the recommendation of this official as to engineering feasibility was seconded by one assuring economic and social feasibility. The fact remains, however, that such recommendations made during a period of agricultural expansion and rising prices may prove disastrous at another part of the cycle. Irrigation district finance is a long-time project.

We have then in western United States a long catalogue of irrigation institutions. Some types of organization are out-and-out wards of the Federal Government. Here Government land is provided with irrigation facilities not because of any immediate necessity for increased crop production but because the settlement of that land is patently desirable and settlement is impossible without irrigation. In another class of organization the initiative comes from the landowners themselves, who in a carefully qualified election, move to bond their land for irrigation improvement. A cynic might wonder how many votes in such an election were won by the thought of increased production and better living conditions, and how many votes were won by the thought of appreciated land values by the proposed irrigation facilities with the possibility of moving out of the district to residence in the county seat.

The irrigation census of the United States, published in conjunction with every general census since the eleventh, gives statistical evidence as to the extension of irrigation facilities in the nineteen Western States by enterprises of these many kinds. In 1889, three and one-half million acres were irrigated. By 1899 the area had doubled. At the time of the thirteenth census this geometric increase was once more in evidence, some 14 million acres being reported as irrigated in 1910. In 1929, this area had increased to 19 million acres. Essentially the same irrigated area was reported in 1930. How much of this rapid falling-off in the rate of irrigation extension in the United States may be charged to the ever-increasing costs of new projects, how much to the inevitable balance between supply and demand, and how much to social and economic implications would form a nice study for one interested in irrigation economics.

We have no corresponding figures for the rate of irrigation development in Hawaii. In fact no compilation of figures relating to areas irrigated was made until 1935. At that time 128,000 acres were reported, or about 0.7 of one per cent of those supplied with water in the States.

In Hawaii we are apt to confuse the words "irrigated" and "irrigable." Irrigated land of course means land which is actually being supplied with water for crop production, while "irrigable" is used to mean land which might be served with water with existing facilities if such land were to be put under crops. With these definitions it is evident that all irrigable land is irrigated in Hawaii, but this is certainly not so in Continental United States. There, the slow rates of settlement of some projects have been a matter of some concern. A scrutiny of figures given in the most recent census indicates that about half the lands of the average irrigation project are actually irrigated in the first 10 to 15 years of its existence, but that the

reclamation of the second half is much slower. The curve for 1930 indicates that a three-fourth development may not be expected before 70 years have passed. The corresponding statement for Hawaii would indicate complete development of irrigable land within the first year.

Other figures culled from the census of 1930 and from local reports of varying origin provide other interesting comparisons. For example, 36 per cent of Hawaii's cropped area is irrigated as compared with 8 per cent for the nineteen Western States. Only four States of the group—Kansas, the two Dakotas, and Oklahoma—irrigate less land than Hawaii in terms of acres, but only seven of those States have spent more money in irrigation development than has Hawaii. From this it follows that it must cost more to provide irrigation facilities for Hawaii than on the Mainland, and indeed it does. By 1935, Hawaii had spent $304 per acre to provide irrigation facilities for its average irrigated acre, a figure which is to be compared with $89 for Arizona, $66 for California, and $64 for Washington, these States standing at the top of the list when arranged in the order of decreasing investment per irrigable area.

Still more spectacular is the comparison between the values of the irrigated crops. In Hawaii the value of the crop from the average irrigated acre was $340 in 1935. The corresponding figure for Washington in 1929 was $151 and for California, $126. From such figures we may derive another comparison with a much more imposing title. This is "irrigated crop income per dollar in water development for each acre irrigated." For Hawaii this figure was $1.11 as compared with $0.87 for the nineteen States. In other words, a dollar per acre invested in irrigation works in Hawaii has resulted in an annual crop income of more than $1.00 per acre as compared with 87 cents for the average enterprises on the Mainland.

It would be folly to suggest that our unique water laws and our local irrigation institutions are responsible for any such record of achievement. Our fertile soils, abundant sunlight, aggressive management and a secure market for a valuable crop have all contributed to the local picture. But the comparison, unrecognized as it may be by Mainland authorities in irrigation administration, still stands.

Alone and unencouraged by Governmental help or subsidy, basing costly ventures upon new and untried water law, believing that irrigation is primarily an aid to crop production rather than a tool to be used toward the end of social progress, our irrigation pioneers have put Hawaii in a place unique in the annals of irrigation. The fact that local achievements in this outpost of American agriculture have so far escaped recognition need not detract from our appreciation of their soundness.

Scientific Irrigation Management

A REVIEW OF INVESTIGATIONS ON PLANT AND WATER RELATIONS

THE WAIALUA IRRIGATION INVESTIGATIONS

THE ADMINISTRATION OF PLANTATION IRRIGATION WATER

By H. R. Shaw and J. A. Swezey

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Foreword

Studies on the interrelation of soil moisture, weather, and crop production reported in the following series of papers are the result of eight years of investigation by the Experiment Station of the Hawaiian Sugar Planters' Association.

The reports cover briefly previous work in Europe, the mainland United States, and in Hawaii on soil moisture as related to plant growth, and describe the steps leading toward the modern conception of plant and water relationships. They touch on fundamental investigations conducted since 1928 at the Makiki station, the Waipio substation, and various plantations of this Association in determining certain basic denominators between the soils of Hawaiian cane lands and the growth and development of the sugar cane plant as affected by soil water.

The reports describe in some detail a cooperative investigation by the Waialua Agricultural Company, Ltd., and the Experiment Station of the H.S.P.A. in which the culminated evidence gained from earlier studies under controlled conditions was applied to commercial cane fields in an endeavor to gain a more efficient use of irrigation water.

The present reports do not purport to be a series of scientific monographs nor an exhaustive analysis of the complex relationships between plant growth, soil moisture, and weather. They will, we hope, provide a guide to the practical application of scientific principles in plantation irrigation and may stimulate further investigation and study of an interesting and important subject.

Some of the material presented has been published previously by one or both of the writers in *The Hawaiian Planters' Record,* in *Proceedings of the Association of Hawaiian Sugar Technologists,* and in mimeographed reports to the plantation members of the Hawaiian Sugar Planters' Association. We have endeavored, in this series of reports, to organize in convenient form the major contributions of workers in Hawaii to the problem of plant and water relations.

We are indebted to many individuals for helpful suggestions and active interest in various phases of the investigations reported here. Prof. H. A. Wadsworth, of the University of Hawaii, is largely responsible for introducing to the Hawaiian Islands the modern philosophy of soil moisture movement and availability, and has been generous in his advice and active participation in all phases of the project. H. P. Agee, Director of the Experiment Station at the time the project was organized, has stimulated the development of the investigations by his suggestions and scientific curiosity. Dr. H. L. Lyon, present Director of the Experiment Station, and R. J. Borden, Agriculturist, have contributed much in energy and sympathy to the project. The accuracy and patience of Y. Matsusaka, who conducted the tests on the wilting percentages of plantation soils, added largely to the valuable results of this work.

Our thanks are also due to F. C. Denison and many others of the Experiment Station staff, to the agriculturists and field staffs of the plantations who contributed to the work, and particularly to J. H. Midkiff, C. B. Butchart, and the staff of division overseers of the Waialua Agricultural Company who have aided the progress of the investigations by their cooperation and interest. Finally, we wish to thank the assistants who, by their loyal devotion in laboratory and field, have provided the basic data described in these reports.

A REVIEW OF INVESTIGATIONS ON PLANT AND WATER RELATIONS

By H. R. Shaw*

The history of irrigation is nearly as old as the history of agriculture itself. Traces of irrigation systems used by forgotten civilizations in Asia, Africa, South America, and southwestern United States indicate that the craft of irrigation is well over 3,000 years old. Irrigation as a science, however, is one of the newer contribu-

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tions to the field of agriculture. The modern conception of the relationship between the soil, plants, and water has existed barely 30 years.

Inevitably, in a new and growing field of investigation, a maze of conflicting theories, hypotheses, and fallacies has arisen to add complexities to an already complex subject. The very fact that various investigators differ so widely in their interpretations of the response of the plant to water, and the fact that the viewpoint toward soil moisture investigations has constantly changed during the past fifty years should be sufficient indication that the results of previous work must be accepted with caution. Even greater deliberation must be made in any attempt to apply the findings of Mainland and European workers to our local conditions. It must be admitted, however, that a background of previous investigations is both desirable and necessary for an intelligent prosecution of any problem.

This paper will attempt to present briefly the major contributions of the past as a foundation to the steps leading toward the best modern thought on plant and water relations. While the paper makes no pretense of being an exhaustive study of research in plant physiology and soil physics for the past century, it should provide some basis for further study by those interested and will serve to indicate the trends and progress of irrigation investigations.

To aid readability, direct citations to the literature are not used in the text. The writer is particularly indebted to N. A. Maximov's excellent book, *The Plant in Relation to Water,* as a source of information on the work of European investigators. A selected list of reference abstracts on the major contributions of American and British workers since 1900 is appended to the report.

Investigations Prior to 1900

Until the present century the absorption and use of water by plants was almost entirely a study by botanists and physiologists. During this period (roughly from 1850 to 1900) in which most of the investigations were conducted in Europe under Pfeffer, Sachs, Vesque, and others, the plant was studied under artificial laboratory conditions in order to observe osmosis and osmotic pressures, root absorption, and other fundamental relationships of the plant and its environment. Valuable as the results of these investigations were in establishing the basic physiological reactions between the plant and water, they left much to be developed in applying the findings to plants in the field.

Sachs, working with tobacco plants in 1859, was apparently one of the first investigators to recognize the relation of plant wilting to moisture inadequacy as a possible function of the soil type. He determined the maximum amount of water which could be held by three different soil types as well as the residual moisture in each soil at the time tobacco plants wilted in a humid atmosphere.

Gain, in 1895, and Hedgecock in 1902, undertaking ecological studies of plants in their relationship to arid and humid regions, apparently found that plants differ in their ability to take water from the soil.

In soil physics, as well as in plant physiology, the tendency was to study reactions under artificial rather than natural conditions. Hence, many of the early investigators used rubber balls, glass spheres, and similar means to illustrate and study the effect of surface tension, capillarity, and other soil and water phenomena. That

many of the principles do not hold when applied to natural soils, and particularly to colloidal soils, has been demonstrated frequently since that time.

Investigations Since 1900

Relation of Plant to Soil Moisture:

It was not until the present century, with the wide development of irrigation and reclamation projects in the western United States focussing attention on the importance of adequate moisture supply, that the study of plant and water relations became a practical as well as an academic field of investigation. Investigations of the past thirty years have been more directly concerned with soil moisture conditions in the field and with the study of crop responses as indicated by the plant itself.

The popular conception of thirty years ago, and one which is still widely accepted in some quarters, is that there is an "optimum" moisture content for each soil type at which a given plant species will obtain maximum growth. This optimum moisture content, which supposedly varies not only with the soil type but with the type of plant grown, apparently cannot be defined in terms of any physical property of the soil nor with the physiological condition of the plant. Cameron and Gallagher in 1908 recognized the "optimum" moisture content, but suggested that it might be a range of moisture content within which the plant might grow equally well. They also made the very important suggestion, based on their experimental results, that this zone of equally available soil moisture might be a physical function of the soil rather than a purely physiological function of the plant.

It remained for Briggs and Shantz, of the United States Department of Agriculture, to publish in 1911 the results of extensive investigations which did much to change the conception of the moisture relations of plants. These investigators studied hundreds of plants of various species in many types of soil. The plants were grown in containers holding a small mass of soil and were so sealed that the only losses of moisture resulted from transpiration through the plant. The residual moisture content of the soil at the time the plant wilted to such an extent that the leaves could not regain turgidity after being placed in a dark humid atmosphere was determined for each of the plants at different stages of its development, under different environmental conditions, and in different soil types.

The results of the Briggs and Shantz investigations indicated that all plants (regardless of age, species, or environment), when grown in the same soil wilted at approximately the same moisture content. On the other hand, the soil moisture content at the time the plant wilted differed widely among different soils, and ranged from extremely low values in sandy soils to comparatively high moisture contents in clay loams.

Such a conception of plant and water relationships as that advanced by Briggs and Shantz was so contrary to general opinion that it was only natural that their results were received with some degree of skepticism both by scientists and by farmers. As has been indicated previously, earlier investigations by other scientists, notably Sachs, Hedgecock, and Gain, indicated that different plants do not avail themselves equally of soil moisture although Maximov points out that these investigators studied plants grown in open porous flower pots in which moisture was probably lost by direct evaporation from the soil surface as well as through the

porous walls of the container. Such a condition would result in unequal drying of the soil, which may have influenced the results.

Exceptions to the Briggs and Shantz theory of a constant wilting point for all plants grown in a given soil type have been made by many plant physiologists, particularly by those associated with the Desert Laboratory at Tucson, Arizona. The general objection by these workers was that the environment in which the plant is grown has a major influence in causing the plant to wilt.

Undoubtedly a distinction must be drawn between temporary and permanent wilting. Temporary wilt may be defined as that stage in which the demand of the plant for water is greater than the power of the roots to supply it or of the plant tissue to transport it from the roots to the region of threatened deficiency. Such a condition would exist when the factors inducing transpiration are so high that the rate of moisture depletion from the plant leaves is greater than the rate of moisture absorption from the soil by the plant roots. At such a stage leaves would lose their turgor, and growth would cease temporarily until the intensity of climatic factors was lowered so that the rate of supply would again equal the rate of demand.

Permanent wilting, on the other hand, is that stage at which leaves will not regain their turgor even under greatly reduced demands by transpiration. Consequently, complete turgor cannot be restored and growth will not be resumed until additional moisture is added to the soil. Thus, the major influence causing temporary wilt is the climatic factors over which we have little if any control; the major influence causing permanent wilting is the amount of soil moisture available for growth. Over this factor we may exert a very definite control.

Brown, in an investigation conducted at the Desert Laboratory, found that the residual moisture in the soil at the time various plants wilted was apparently influenced by the environment in which they grew. Plants grown in small pots under direct sunlight wilted at a higher moisture content than plants of the same species grown in a humid room. Brown apparently did not distinguish between temporary wilt and permanent wilt which was defined by Briggs and Shantz as the state at which the leaves could not regain turgidity after being placed in a dark humid atmosphere. Brown felt, however, that his results were not incompatible with those of Briggs and Shantz since he stated, "The results of Briggs and Shantz are applicable, providing that wilting occurred under the same general environmental complex under which the plants have been grown."

Caldwell, working at the same station, states that the residual soil moisture at permanent wilting of a plant varies not only with the environmental conditions but with varying evaporation rates of the atmosphere. This investigator endeavored to distinguish at what hour of the day plants first enter the wilting state. In studies conducted in a dry, hot atmosphere where transpiration losses are great, and with the determination of wilting based on ocular judgment, this degree of refinement would appear to demand powers of observation beyond the ordinary.

Shive and Livingston seem to find that the age and development of the plant was not an important factor in the degree of soil moisture depletion, but that the soil moisture content at permanent wilting varied with the intensity of evaporation. It should be observed that all three investigations mentioned above were conducted at the Desert Laboratory in Arizona. It would appear probable that the environmental

factors under which the experiments were conducted might be considered as an extreme so far as excessive transpiration and evaporation rates are concerned, although the authors mentioned made some attempt at artificial control of light intensity.

More recent investigations in California and the Middle West tend to support the theory of Briggs and Shantz that all plants grown in a given soil undergo permanent wilting at approximately the same soil moisture content. Veihmeyer and his colleagues in California studied the growth and wilting characteristics of annual plants and fruit trees in small containers, in large tanks weighing over 2,000 pounds, and in the field. They substantiated the major premise of Briggs and Shantz in finding that the permanent wilting percentage is fundamentally a function of the soil type. These workers also improved and standardized experimental procedure in plant and water investigations, and contributed greatly to the application of research to commercial irrigation in California.

Water Requirements of Crops:

The amounts of water required to raise various crops to maturity received the attention of many workers during the early part of the century. Much of this research was conducted by growing isolated plants in small containers and determining the amount of water required to produce a given amount of grain or of dry matter. The results of such studies were local in application and were so greatly influenced by weather and general growing conditions from year to year as to be of limited value to agriculture. In addition, the effect of root-binding, water distribution, and excessive evaporation and transpiration in pot studies usually conducted in the greenhouse may have given results far from comparable to field crops grown under natural conditions.

Another type of study which flourished in early investigations and which is occasionally reported at the present time attempts to vary the soil moisture percentage in a series of pots holding the same type of soil. By adding successively larger amounts of water to each pot treatment, the investigator assumes that he has "maintained" each pot at a different soil moisture content, and that the resulting plant yield from each treatment indicates the soil moisture content best suited for the growth of the plant in that soil type. It will be demonstrated later in this report that each soil has a definite capacity for water and that it is a physical impossibility to irrigate a soil to a uniform soil moisture content other than its field capacity. Attempts to control the moisture content by adding different amounts of water to the surface result merely in completely wetting the soil to various depths.

Field studies on the water requirement of various crops have also been conducted. Usually the tests consist of careful measurement of water to small plots, and the determination of the ratio of irrigation water to the final weight of the crop. In general, such tests have shown that the better the conditions of soil moisture and fertility, the less the water requirement of the plant. No conclusive evidence has been presented to show that fertilization changes the moisture-holding properties of the soil, although many investigators have observed that the development of the root system, and consequently the extent of the soil moisture reservoir from which the plants feed, have been favorably affected by fertilization.

Single-Value Soil Constants:

The possibility of determining a single-value constant which would express the nature of a given soil as well as its properties in relation to agriculture has long been a fertile field of investigation.

The hygroscopic coefficient, defined as the percentage of water held in a soil initially dry which has been brought into a saturated atmosphere received the attention of early workers in Germany, Great Britain, and by Alway and his colleagues in Nebraska. The early investigators held that the hygroscopic power of the soil rendered water of the atmosphere available to plants, but subsequent research demonstrated that hygroscopic water was valueless in supplying moisture to growing plants. The difficulties of maintaining constant conditions of temperature and humidity, and the length of time required to make the determination have led to the general abandonment of the hygroscopic coefficient in agricultural investigations.

The use of the maximum water-holding capacity of soils was another attempt to obtain a single-value soil constant. This was a laboratory determination in which soil was placed in small brass tubes, saturated by standing in water, and allowed to drain for a definite length of time. The resulting soil moisture content was termed the "maximum water-holding capacity" and some proportion of it, usually 60 per cent, was considered the "optimum" moisture content of that soil. The analysis is affected by the way the soil is packed, the height of the soil column, and the temperature. This procedure is no longer in general use.

British workers, especially those in the Dominions, have a single-value soil constant called the "sticky point" and defined as the moisture content of heavy soils at the point of adherence without excess water. Hardy of Trinidad and Tempany of Mauritius also use the "shrinkage coefficient" as a measure of soil plasticity and colloidal content.

The volume weight or apparent density of soil is another single-value constant which, although presumably unaffected by soil moisture, is of importance in determining irrigation requisites of different soils. Various laboratory methods of analysis for this constant are objectionable due to the disturbance of the soil column when moved from the field to the laboratory. A number of methods have been developed for determining the volume weight in the field and expressing the result as the weight of soil per unit volume in terms of an equivalent weight of water.

The soil constant which has found greatest favor among American workers due to its rapidity and simplicity is the "moisture equivalent." This is also a laboratory procedure by which small samples of saturated soil are subjected for a definite length of time to a centrifugal force 1,000 times the force of gravity. The residual soil moisture content is termed the moisture equivalent.

The moisture equivalent and its procedure was first developed by Briggs and McLane, of the United States Department of Agriculture, in 1910 when the investigations on the soil moisture content when plants wilt, previously described, were being conducted. The Washington investigators found that a definite relationship existed between the moisture equivalent and the moisture percentage of that soil when plants wilted. This relationship was expressed by dividing the moisture equivalent by the wilting percentage. A ratio which averaged 1.84 was found for all soils used in the original investigations of Briggs and Shantz. Later research by

other workers, particularly by Veihmeyer and Hendrickson in California, indicates that in certain soils the ratio between these two factors may vary considerably. When applied to soils of the same geologic origin or geographic location, however, the moisture equivalent has proved to be the best available single-value constant for the relative classification of soils and for an indirect estimate of the soil's range of available moisture.

Movement of Soil Moisture:

In no phase of soil moisture investigations has there been more important progress than in studying the movement of water in the soil. As has been previously indicated, early workers in soil physics attached great importance to capillary action as a force in moving water from moist to dry soils. Such studies were conducted chiefly in the laboratory, using artificial substitutes to simulate the soil grains, and were concerned with mathematical analyses of the effect of viscosity, surface tension, and moisture-film curvature on the rate and extent of water movement.

Unfortunately the results of much of this research in artificial media was extrapolated to field soils, and a misconception of the relation of water and soil was created in the minds of scientists and farmers alike.

The value of capillarity in supplying plants with water from adjacent masses of moist soil frequently has been disproved. As early as 1889, King of Wisconsin noted the slow rate of capillary rise in a soil and doubted the ability of this force to supply plants with water unless the roots were in or close to the underground water table. He observed specific cases in which corn suffered from inadequate soil moisture although the roots were only 42 inches above the water table. Loughridge of California reported in 1894 that capillarity was extremely limited in extent and rate unless the soil surrounding the feeding roots was in immediate contact with a free-water table.

The advent of "dry farming" in the Great Plains again emphasized the ineffectiveness of capillarity in supplying water to plants. Burr in Nebraska found that "The movement of water thru the soil by capillarity is so slow that it is practically useless in bringing water from a lower soil area for the use of a growing crop"; while Thysell in North Dakota states, " . . . because of the absence of a free water table capillarity as a force for moving water upwards ceases and is of no practical importance."

The detrimental effect of surface evaporation in depleting soil moisture was also stressed by early agricultural workers who reasoned that as capillarity constantly moved water from the relatively moist subsoil to the surface, the greater part of the soil's water supply would be lost. The value of the soil mulch was therefore emphasized as an effort to prevent losses of moisture by evaporation. Repeated investigations by many workers, however, indicate strongly that surface evaporation in a normally compact soil without cracks is limited to the first few inches on the surface. Below this depth, water is removed from the soil in only one way—by the feeding of plant roots.

Alway, from studies in the Saskatchewan, concluded that roots go to the stored water in the subsoil instead of the latter being elevated by capillarity and that comparatively little water which has once passed below the plant is lost by evaporation.

Thysell came to the conclusion that the increased moisture content attributed to the soil mulch is due to the eradication of weeds. Otherwise the soil mulch can be disregarded. Veihmeyer of California, working with large tanks and with field plots, compared the moisture losses of cultivated areas with those of uncultivated areas in which weed growth was suppressed. He found that cultivation did not influence the losses of moisture by evaporation from the bare surfaces of soils nor did it materially influence the distribution of moisture in the soils.

A wealth of evidence by many other workers could be offered to support the belief that both capillarity and surface evaporation have little if any effect on the movement of moisture in normal well-drained soils, and that essentially the only means of soil moisture reduction in the soil is by root feeding and transpiration of cultivated plants and weeds.

The downward movement of water after irrigation or rainfall is of particular interest to the farmer. The accurate study of the factors involved can be made only in the field, as the laboratory investigations with artificial or disturbed soil often have led to erroneous results and impressions. The firmly established belief in the power of capillarity and surface evaporation, even in the face of evidence demonstrating its slight or non-existent effect, also tended toward a confused picture of soil water movement.

King, of Wisconsin, noted a very slow rate of penetration after a 1.4-inch rain, explaining the results on the basis that cultivation kept the soil cooler below the surface, strengthened capillarity, and tended to decrease the downward percolation of water. Loughridge, in 1908, found the downward movement of irrigation water to be very irregular in rate of movement as well as in the amount retained at various depths. He also observed in furrow irrigation that the water did not move laterally more than two feet. Many investigators now feel that the movement of soil water does not cease until equilibrium is established with the water table, although the time required for this adjustment to take place may be so great that it is of little benefit to growing crops.

A direct method of studying the movement of soil moisture after irrigation is that of cutting a trench across one or more irrigation furrows after water has been run for a definite length of time in the furrows. The extent of downward and lateral water movement can thus be observed and marked on the cross-section of the trench. Most workers who have used this method find that a rapid movement of moisture through the soil takes place for only a short time after water has disappeared from the surface, and soon reaches a state of equilibrium from which there is no significant movement of moisture. The vertical penetration of water is much greater in rate and extent than the lateral movement in uniform well-drained soils. The line between moist soil and dry soil is generally sharply defined. Veihmeyer has carried this method of study a step further by obtaining samples for total moisture and for moisture equivalent in the moist and dry areas of the furrow cross-section. He finds that *all* of the soil in the moist area holds the same proportion of water, which is essentially equal to the value of the moisture equivalent of that soil; while all of the soil in the dry area, even in that close to the dividing line, is relatively dry and shows no increase in moisture content which can be attributed to the current irrigation.

Surface Forces of Soils:

Still another phase of investigation which has received attention in Great Britain and the United States has been the study of the forces in the soil which influence its power to retain water. In general, the conclusions of many workers using various methods of analysis point to the fact that the water in a well-moistened soil is very loosely held by the surfaces of soil grains. As the soil dries out, the forces holding the water continue to be slight until a critical moisture content, dependent upon the nature of the soil, is reached. At this critical point, water is held by the soil with increasing tenacity and for each further increment of water loss the force tending to bind the water to and around the soil granules increases tremendously.

The significance of surface-force research to agriculture is that the soil moisture content at which the soil forces become increasingly effective is essentially the same as the permanent wilting percentage of that soil. Water is equally available to the plant from the time of irrigation to the time the wilting percentage is reached, after which soil water becomes increasingly difficult for the plant to obtain until it becomes entirely unavailable for growth.

Modern Conception of Plant and Soil Moisture Relations:

Thus, nearly a century of intensive investigation by many workers has led to a generally accepted conception of the relation of soil moisture to plant growth. Supported by many careful studies, these general statements may be summarized as follows:

1. *Each soil has a definite capacity for moisture which is inherent in the physical structure and chemical nature of that soil and does not change with season nor with the plant species grown therein.*

2. *After the soil surface is wetted by rainfall or irrigation, water moves downward by gravity and fills each increment of soil to capacity before lower increments receive any water. The depth to which rainfall or irrigation is effective is dependent entirely upon the physical capacity of the soil and the amount of water added to the surface.*

3. *In the absence of a free-water table a short distance below the surface, capillarity is not effective in moving water from a moist to a dry soil.*

4. *Surface evaporation reduces the moisture content of a normal compact soil to a depth of only a few inches. Cultivation and mulching as a means of conserving moisture below this surface layer are effective only in their ability to suppress weed growth.*

5. *Moisture can be drawn from the soil only by the feeding action of plant roots. Plant roots will not develop and extend in dry soil.*

6. *The rate at which moisture is drawn from the soil is dependent upon the nature of the plant, the leaf area exposed and the evaporating conditions of the atmosphere.*

7. *When the soil water has been reduced to a critical moisture content, commonly termed the permanent wilting percentage, plants obtain water with increasing difficulty, leaves wilt, and normal plant performance is severely handicapped or entirely stopped until the soil is again filled with water.*

8. The permanent wilting percentage is a function of the soil type and does not vary with season nor with the species and age of the plant.

9. In soils of similar geologic origin and geographical location, a laboratory analysis called the moisture equivalent provides an index of the physical nature and indicates indirectly the maximum and the minimum limits of readily available moisture in that soil.

Investigations in Hawaii

The lateritic nature of Hawaiian soils adds further complications to the study of soil and water relations. As early as 1894, Hilgard and Loughridge noted the unusual characteristics of soils from the "Sandwich Islands," and added "The moisture coefficient is extremely high in all soils examined."

Early Research of Maxwell and Eckart:

One of the first soil properties studied by Dr. Walter Maxwell, first Director of the Experiment Station, H.S.P.A., was the power of Hawaiian soils to absorb and retain moisture. In 1896 he reported the results of a study on 20 samples of Hawaiian cane soils from the islands of Oahu, Maui, and Kauai which he packed in metal cylinders, immersed in water, and determined the amount of water absorbed and retained. While Maxwell recognized that the tests ". . . do not state the behavior of the soils in their places in the fields . . . ," the fact that the absorptive power of the soils varied from 31.8 to 86.9 per cent led him to emphasize that ". . . organic matter is a predominating factor in the relation of soils to water" and that there is ". . . an absolute need of first determining the absorptive power of each soil before the application of water."

Maxwell also conducted studies on the transpiration of cane plants grown in tubs over a free-water table. His results led him to the conclusion that cane grown under the conditions of the experiment transpired nearly 2½ times as much water at the age of six months as it did during the first month of growth. Transpiration of the cane plant was nearly twice as great during hot sultry weather as it was under normal trade-wind conditions although evaporation from a bare soil surface was greater under the latter conditions.

Schuyler and Allardt, civil engineers investigating water supply and requirements for new plantations in Hawaii, made the following interesting comments on irrigation practice on leeward Oahu in 1889: "Three waterings a month is the least that is considered safe to apply to keep the cane growing without check. In localities corresponding in position and climate with Honouliuli it is customary to maintain this periodical irrigation regardless of the rainfall. The rain may at times exceed the quantity applied artificially, but irrigation is performed as usual notwithstanding, in order that there shall be no break in the continuity of the waterings. It seems to be generally understood by all planters that the depth of each watering shall be at least an average of 3 to 4 inches over the whole surface." These writers also stated that the general manager of the plantation at Spreckelsville added that within reasonable limits it was almost impossible to put on too much water and that the more water applied the greater the yield.

Maxwell took exception to the low duty of water reported by the early plantations and conducted small plot experiments over a period of three crops from 1897 to 1900 in which he produced better than 12 tons of sugar with 2.5 million gallons of water as compared to plantation reports of less than 6 tons of sugar for 5 million gallons of water. Maxwell adds, "The . . . data show what has been done and what it is possible to do, where the irrigation is carried out according to scientific principles and where the conditions are under control. Upon a large plantation the conditions cannot be controlled to the same extent as is possible with experiments on limited areas. This in no wise lessens the force of the fact that plantations are wasting huge volumes of water in their practice of irrigation or removes the necessity of . . . determining the location and causes of the waste."

Lysimeter tests conducted at the same time led Maxwell to state, ". . . only so much water can be put on [the soil] without its being wasted. . . . These facts tell us that if we put on more than a given quantity of water the soil cannot hold it." Eckart continued the field plot experiments from 1903 to 1905, varying the amounts of water to five plots planted to Lahaina and Rose Bamboo varieties of cane. Apparently the treatments were continued regardless of the season or weather conditions.

Attention to irrigation requirements and the effect of water on sugar cane lapsed after 1905, although H. B. Penhallow suggested in 1913, "A scientific study of our soils with a view to determine how much irrigation they will stand and how much water is necessary to produce a given quantity of sugar will give as sure a return as any improvements which have been made in the process of manufacture."

Work of Allen at Waipio Substation:

The first program of intensive study on the relation of soil moisture to crop production was conducted by R. M. Allen at the Waipio substation from 1916 to 1920. He traced the extent of soil moisture movement in Waipio soils by auger sampling, and concluded that it was impossible to store, in the upper six feet of a Waipio soil, more than 4½ inches of water, of which about 2½ inches was retained by the surface two feet of soil. Practically the same amount of water was retained in the soil regardless of the amount of irrigation water applied.

After completing an irrigation experiment in which the amounts of water per acre per crop varied from 2.45 to 8.79 acre-feet without obtaining any significant difference in cane yield, Allen observed, "The true value of an irrigation is measured not by the amount of water that is applied to the soil, but by the amount of moisture that is retained by the soil and the manner in which this is distributed throughout the soil area both laterally and perpendicularly."

The first approach locally to the present conception of the wilting percentage was reported by Allen when he stated in 1919, "We have found that on our medium soil at Waipio whenever cane looks as if it needed water, the moisture percentage is below 23%. This means that when our moisture percentage gets as low as 25% it is time to irrigate, for we should not wait until the cane is suffering before we apply water, for at such time its growth is checked." He noted further that the appearance of the soil or of the plant is not a proper criterion of the time to irrigate.

Allen's work on soil moisture at Waipio apparently stimulated interest in irrigation investigations throughout the Islands, and a number of plantations conducted experiments based on soil moisture observations.

H. W. Baldwin of Maui Agricultural Company observed in 1920: "It has frequently been said that seepage water is not lost to the cane, but eventually finds its way to the roots. . . . In order to test out this point, soil moisture tests to a depth of 6 feet were made at one-foot intervals distant from a dry watercourse. . . . and water allowed to run in the watercourse for an hour and fifteen minutes. Two days later soil samples were again taken and it was found that the soil moisture at a distance of one foot from the watercourse had increased 3.85% ; two feet away, 3.12%, and three feet away, only 1.04%, thus showing that the lateral penetration was very slight. . . ."

Work of Alexander at Ewa:

W. P. Alexander at the Ewa Plantation conducted soil moisture observations on three different soil types from August 1921 to April 1922. He concluded that the maximum which could be retained by these soils was about 30 per cent and that ". . . irrigation water applied after this point is reached is wasted." His data showed, ". . . practically no capillary movement of the water from the lower feet to upper strata of soil. The drying out process proceeded downward, being rapid in the first two feet." By observation he set the wilting point of cane as below 21 per cent, and added, "This might be called the danger point, above which soil moisture must be kept to maintain normal growth. To allow the soil moisture to reach this point before applying irrigation water would be retarding the growth of the cane plant."

Interval Tests:

Alexander pointed out some of the difficulties of obtaining representative soil moisture samples in the field, and turned in 1923 to the development of the "interval test" as a means of gaining information on the irrigation requirements of their plantation soils. These experiments compared the growth, water consumption, and yields under three irrigation treatments in which the variable was the length of time between irrigations. By a maximum treatment, the cane received frequent irrigations at a rate more rapid than was popularly considered practicable with the irrigation methods and available water supply in use; a normal treatment supplied the cane with adequate irrigations as based on the best conditions the plantation could offer; and by a minimum treatment, irrigations were made as seldom as possible without allowing the cane to die. A fourth treatment—plantation practice—by which irrigation water was applied at the same time as that to the surrounding field, was occasionally added. The interval between irrigations to each plot series was determined somewhat arbitrarily by past experience and collateral investigation.

The success of the interval tests at Ewa led to their adoption on other plantations, particularly those of the Pioneer Mill Company, Koloa Sugar Company, and Lihue Plantation Company. The relative merits of the interval test as a means of irrigation investigation do not need analysis here. The experiments were of direct value to many of the plantations, provided a rapid and relatively accurate method of estimating the water requirements and rate of irrigation in various areas, and stimulated a renewed interest in irrigation studies and the evaluation of water.

Irrigation Investigations at Waimanalo:

A collaborative irrigation experiment between the Experiment Station and the Waimanalo Sugar Company was started in June 1923 and compared plantation practice with "complete irrigation" on large plots in two typical fields of the plantation. Soil moisture sampling and cane growth measurements were used as criteria of irrigation. The reports on the project emphasize the different moisture requirements of various soils of the plantation. The Waimanalo tests emphasized again the results obtained by Allen at Waipio: "The true value of an irrigation is measured not by the amount of water that is applied to the soil, but by the amount of moisture that is retained by the soil and the manner in which this is distributed. . . ."

The Waimanalo investigations turned from soil moisture and cane growth determinations toward the measurement of field consumption and seepage losses over the plantation although Beveridge noted in 1927 that soil moisture sampling was still used as a field guide, ". . . the beginning and end of the irrigation season is largely decided by means of soil moisture determinations. Irrigation commences in the spring as soon as the soil moisture has dropped appreciably below the optimum point in many of the fields. In the same way the season is closed in the fall, when the soil moisture has increased and the appearance of the cane indicates an adequate supply of water in the soil."

Irrigation Studies by Oahu Sugar Company:

The Oahu Sugar Company in 1924 inaugurated a program of irrigation investigations which included studies of soil moisture and cane growth relationships in four fields of widely varying soil types. The studies were especially concerned with the soil moisture content required for maximum growth. The approach to the present conception of the wilting percentage as a function of the soil type is shown by the following extract from a report in 1928 by the plantation agriculturist, William Wolters, who stated that in each of four typical fields, ". . . check plots (plantation practice) are compared with control plots. The check plots are irrigated at the same time as the surrounding crop cane. The control plots are irrigated . . . whenever . . . the soil moisture content reaches a 'zero point' which, by experimentation, calls for an application of water. The 'zero point' is not a fixed figure, since it is governed by seasonal variations. This point is established as a result of past experience, based on soil type, irrigations and rate of growth. Each soil type has its own 'zero point.' "

The arrival in 1928 of Prof. Wadsworth of the University of Hawaii and his affiliation with the Experiment Station in an advisory capacity, stimulated renewed research on plant growth and soil moisture. Prof. Wadsworth, from his familiarity and association with the work of Veihmeyer and others in California, aroused general interest in the modern conception of plant and water relations which the independent plantation studies previously described had approached. In 1929, Wadsworth and Das repeated the procedure of Briggs and Shantz in determining the permanent wilting percentage of a Waipio soil and discovered that the wilting percentage for beans, sunflower, and sugar cane in the soil used was essentially equal. They noted, however, that cane leaves do not exhibit the obvious symptoms of wilt shown by other plants, and judged the wilting percentage when cane was used as the indicator plant by the soil moisture content at which a change in the transpiration rate occurred.

The Waipio investigations, described separately in this report, were conducted from 1928 to 1932, and attempted to determine the important soil moisture constants of Hawaiian plantation soils as well as to establish the basic principles on which Hawaiian soils compare with those of other parts of the world. In general, the investigations demonstrated the fact that the modern conception of plant and water relations is applicable to the soils of Hawaii and that the general laws governing the movement and availability of soil moisture are universal in their application.

Studies by the Association of Hawaiian Pineapple Canners:

The Experiment Station of the Association of Hawaiian Pineapple Canners also became interested in the application of soil moisture relationships to their plantation soils. Farden analyzed the soil moisture constants of three pineapple soils from the island of Oahu. He found a ratio between moisture-holding capacity and moisture equivalent of 1.11, and between the wilting percentage, using sunflower and peas as indicator plants, and the moisture equivalent of about 1.45. Dean and Abel determined the volume weight of the topsoil and subsoil of a number of pineapple soils. Wadsworth attempted to determine the wilting point of pineapple plants but found that the physiological structure of the plant did not permit obvious symptoms of wilt.

Work of Penhallow at Honolulu Plantation Company:

The first application of the modern conception of soil moisture relationships to plantation field experimentation was made by Penhallow at Honolulu Plantation. He grouped the soils of the plantation into three general classes, based on the moisture equivalent. Periodic soil moisture determinations and growth measurements were taken in representative areas of each soil group, and the rate of soil moisture depletion and the growth rate of the cane determined throughout the progress of the crop. He also conducted an experiment in which the value of various depths of irrigation penetrations were compared. Water was applied when the soil moisture reached an arbitrary minimum of 25 and 30 per cent for red residual soils and of 35 and 40 per cent for adobe soils.

From his data, Penhallow concluded that for residual red soils, "Penetration of irrigation water to a depth of two feet below the surface of the soil is sufficient for the plant's needs and results in water economy. . . . It seems better for the crop in both yield of cane and water economy to allow the soil to dry out to a minimum average moisture content of 25% before re-irrigating. A minimum moisture content between 25% and 30% may be better than either." It should be observed that from the Waipio investigations, which found an average ratio of 1.25 between moisture equivalent and permanent wilting percentage for all soils examined, the predicted wilting percentage from the moisture equivalent values reported by Penhallow should be about 28.0 per cent.

The results of the Honolulu Plantation investigation led to the establishment of a schedule of irrigation intervals for the plantation fields based on the soil type, season, and time the crop started.

An irrigation experiment based on a recent suggestion by Das was installed at the Waipio Substation in 1936. Das suggests that the interval between irrigations may be indicated by the maximum temperature, with an application of water being made when the accumulated day-degrees (daily maximum temperature less 70° F.) from

the last irrigation reaches 200. The experiment is designed to study the effect on cane growth and yield of cane and sugar from irrigations spaced on the basis of 150, 200, and 250 elapsed day-degrees, as well as a comparison with plots irrigated whenever the soil moisture is reduced to the wilting percentage. The success of the experiment is dependent upon a high correlation between maximum daily temperature and the rate of plant transpiration or soil moisture depletion. The results will be watched with interest.

Waipio Investigations on Plantation Soils:

A series of correlated experiments on the basic relationships existing between soil moisture and cane growth on typical Hawaiian cane land soils was conducted at the Waipio substation from 1928 to 1932. The investigations were designed to study whether or not, and to what degree, the conception of plant and water relationships evolved in fifteen years of investigation on Mainland soils applied to the lateritic soils of Hawaii.

Soil Moisture Constants: The first phase of the investigation was to determine some of the fundamental soil moisture constants of widely varying soil types from the islands of Oahu, Maui, and Kauai. Determinations of the maximum field capacity were made by auger samples at interval depths of one foot to a total depth of six feet. The sample area was flooded, 12 samples per foot of depth taken 48 hours after flooding, and the moisture content determined in the Waipio substation laboratory. Volume weight analyses were made at the same time by determining the oven-dry weight of all the soil removed from a one-foot boring and the weight of oil of known specific gravity required to fill the hole. The volume weight was expressed as the ratio of oven-dry soil weight to the weight of an equal volume of water. Samples for moisture equivalent and wilting percentage determinations were taken from the field at the same time, the analyses being made at the Waipio substation.

The volume weight of 105 determinations at various soil depths in 25 plantation fields were comparable to each other in their trend. With normal loam soils of fairly even texture, a low volume weight of 1.0 or less exists in the topsoil within the limits of plowing. The volume weight below this point increases rapidly to a value ranging from 1.1 to 1.5 in the third to six foot of depth. Below the second foot, the volume weight of each depth increment is rather constant in most soils. Kauai soils, in particular, show a marked difference in volume weights between topsoil and subsoil. The volume weights of Hawaiian soils studied are not widely different from those reported in the literature on soils of other geologic origin in Europe and Mainland United States.

The moisture equivalent, on the basis of 133 comparisons in the 25 soil types studied, appeared to hold considerable promise as an index of the physical structure of the soil and particularly as a consistent measure of the soil's capacity for holding water. The relationship between the moisture equivalent and the maximum field capacity was surprisingly consistent over a wide range of soil types, the best value being moisture equivalent x 1.1 = maximum field capacity. Subsequent studies on well-weathered soils of the unirrigated Hilo and Hamakua districts of Hawaii, however, do not show a consistent relationship between the moisture equivalent and other soil moisture constants. The relationship between moisture equivalent and maximum field capacity is shown graphically in Fig. 1.

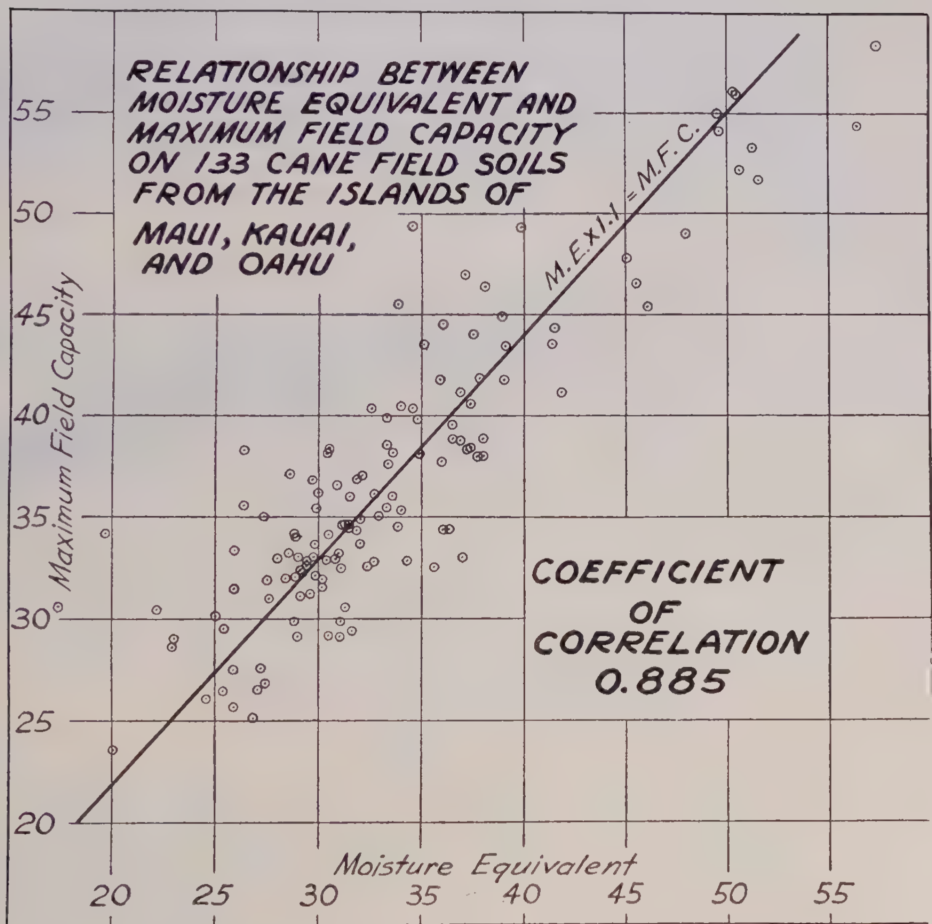

Fig. 1. Relationship between moisture equivalent and maximum field capacity on 133 cane field soils from the islands of Maui, Kauai, and Oahu.

A summary of the soil moisture properties analyzed for 25 plantation soils is given in Table I.

TABLE I

SOIL MOISTURE CONSTANTS OF TYPICAL HAWAIIAN CANE LAND SOILS

Plantation	Field	Elevation	Color	Character	Depth Sampled	No. of Samples	Volume Weight	Max. Field Capacity	M. E.	RATIO Max. Field Capacity ÷ M. E.
Oahu Sugar Co.	38	300′	Red-Brown	Light, Pervious	6′	72	1.13	34.5	30.8	1.10
Oahu Sugar Co.	53	600′	Dark Red	Medium heavy	6′	72	1.19	34.5	31.2	1.11
Oahu Sugar Co.	3A	315′	Dark Red	Fine	6′	70	1.24	33.7	30.6	1.10
Ewa Plantation Co.	"A"	59′	Brown-Black	Heavy	5′	60	1.34	26.1	25.7	1.02
Ewa Plantation Co.	22C	24′	Red over Coral	Light	1′	24	0.43	43.6	35.1	1.24
Ewa Plantation Co.	20A	45′	Black	Heavy	2′	13	0.71	34.1	30.5	1.12
Waimanalo Sugar Co.	26	5′	Black	Heavy	3′	66	0.58	57.2	56.7	1.01
Waimanalo Sugar Co.	18	150′	Dark Brown	Medium	6′	71	1.09	52.9	49.8	1.06
Waimanalo Sugar Co.	13	50′	Black	Heavy	4′	48	1.02	49.3	48.0	1.03
Pioneer Mill Co.	32D	150′	Red	Coarse	6′	72	1.16	34.5	29.8	1.16
Pioneer Mill Co.	LA6	900′	Light Red	Fine	4′	42	1.02	36.0	32.1	1.12
Pioneer Mill Co.	B2	1200′	Dark Red	Medium heavy	6′	71	1.11	36.8	32.6	1.13
Pioneer Mill Co.	B8	650′	Red	Medium	6′	72	1.20	31.6	28.8	1.10
Haw'n Com'l & Sugar Co.	"P"	....	Red	Medium	6′	72	1.11	37.6	32.4	1.16
Haw'n Com'l & Sugar Co.	2	250′	Brown-Black	Coarse	6′	72	1.18	29.5	25.2	1.17
Haw'n Com'l & Sugar Co.	"A"	40′	Red	Medium	6′	71	1.19	37.3	31.1	1.20
Haw'n Com'l & Sugar Co.	"L"	140′	Brown	Medium	2′	24	0.90	28.4	25.2	1.13
McBryde Sugar Co.	20B	550′	Dark Brown	Fine	6′	72	1.17	44.0	40.2	1.10
McBryde Sugar Co.	13D	400′	Dark Brown	Fine	6′	72	1.23	37.9	36.9	1.03
McBryde Sugar Co.	3A	160′	Red	Fine	6′	72	1.25	37.0	31.5	1.17
Lihue Plant. Co.	20H	350′	Dark Brown	Medium	6′	72	1.12	46.5	37.8	1.23
Lihue Plant. Co.	20L	207′	Red-Brown	Granular	6′	72	1.20	39.4	37.4	1.05
Lihue Plant. Co.	30	95′	Dark Red	Medium	6′	71	1.43	31.4	30.8	1.03
Kekaha Sugar Co.	421	750′	Red	Medium	6′	72	1.15	32.2	32.8	0.98
Kekaha Sugar Co.	20	5′	Brown-Black	Heavy	4′	63	0.83	47.7	45.0	1.05

Movement of Soil Water: Laboratory and field tests were conducted on the vertical and lateral movement of water in the soil after an irrigation. Detailed results of the experiments were reported in *The Hawaiian Planters' Record* for January and April, 1932.

To determine the extent of vertical water movement in a soil, a Waipio soil of 35 per cent field capacity was oven-dried, and packed in five waterproofed cardboard cartons. Various amounts of water, sufficient to bring the average moisture content of the soil to 10, 20, 25, 30 and 40 per cent respectively, were added to the soil surface. After 48 hours the cartons were cut open at one-inch increments, and the distribution of the water studied by observation and by obtaining the moisture content of each soil increment. The results were as shown in Fig. 2.

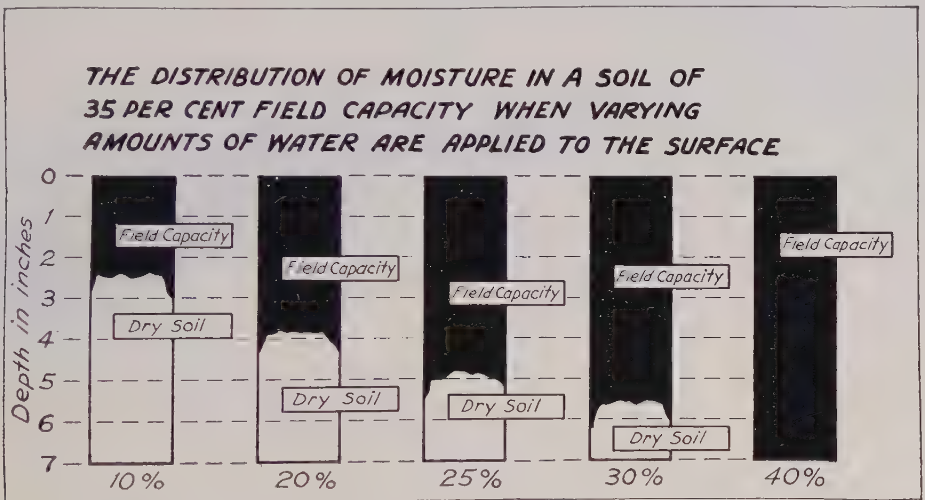

Fig. 2. The distribution of moisture in a soil of 35 per cent field capacity when varying amounts of water are applied to the surface.

Obviously the distribution of moisture throughout the soil mass when a predetermined weight of water is added to the surface is far from uniform. Apparently a given soil has the capacity of holding around its granular structure a certain quantity of water. When the surface increment of dry soil has satisfied its capacity for moisture, water descends to the next lower soil increment, where sufficient moisture is absorbed to satisfy the capacity of the second increment. This sequence is continued until all of the water is held by the soil. The soil at the lower depths receives little if any water until the absorbing power of the upper increments has been satisfied.

Field studies on the distribution of soil moisture under different methods of irrigation were made at the Waipio substation on contour irrigation, at Waimanalo on long-line irrigation, and at Ewa Plantation on the border method of irrigation. Forty-eight hours after irrigation, a trench was cut athwart the furrow or border at various distances from the headgate. The dividing line between moist soil and relatively dry soil was usually clearly defined on the cross-section of the furrow. The outline of the wetted soil zone was marked by nails thrust in the soil, and plotted on cross-section paper. Soil samples for total moisture content and for the moisture equivalent were taken inside and outside the moist area, and the results expressed as

"Relative Wetness" or ratio between the moisture content of the soil after irrigation and its capacity for water as measured by the moisture equivalent. Soil samples were taken repeatedly from the area just below the dividing line for several days after the irrigation to learn if any further movement of water by capillarity had occurred. This method of study, frequently used in Mainland investigations, was first employed locally by T. K. Beveridge of the Waimanalo Sugar Company.

Typical examples of such field studies on soil water movement and distribution are shown in Figs. 3, 4 and 5 for each of the irrigation methods studied. The more important results of these studies may be summarized as follows:

1. Factors which appear to have direct bearing on the distribution of soil moisture after irrigation are: the nature, depth, and texture of surface soil and subsoil; the slope and gradient of the land; and the depth of the free-water table below the ground surface. The nature and depth of the subsoil below the surface appear to have a decided effect on the shape of the wetted zone.

2. After a light irrigation to a normal loam soil by the contour or long-line methods of irrigation, the wetted area is elliptical in shape with its major axis in a horizontal direction. With heavier applications of water, the lateral spread of water does not increase materially but the vertical penetration increases proportionately to the intensity of the surface application.

3. The soil at all points within the wetted area caused by the irrigation is at its maximum field capacity. The soil immediately outside the perimeter of the wetted zone is considerably below its field capacity, and in all probability receives no water from the current irrigation.

4. In a well-drained loam soil, there is no appreciable movement of water from moist to dry soil by capillary attraction, within the short-time intervals involved.

5. Under the contour and long-line methods of irrigation, the lateral penetration of water in the soil does not exceed 30 inches and is seldom more than 20 inches on either side of the center of the furrow.

6. Under border irrigation, the size and shape of the wetted soil zone after the irrigation is dominated chiefly by the permeability of the soil to water, by the slope, and by the side-to-side gradient of the border.

Studies on the Wilting Percentage: The determination of the permanent wilting percentage of a number of plantation soils was made in 1929 and 1930. In brief, the method of determination consisted of growing sunflower plants and small cane plants in pots containing a known weight of dry soil. The pots were sealed so that moisture losses could be attributed only to transpiration through the plant. The soil moisture content at the time the plants appeared to suffer from inadequate soil moisture was determined from the weight of the system. The point of suffering was determined from the appearance of the leaves in the case of sunflower, and by actual measurement of the cessation of growth in the cane plants. A detailed discussion of the methods, which follow essentially those of Briggs and Shantz, Veihmeyer and others in similar studies elsewhere, is contained in a mimeographed report issued in May 1931, to plantation members of the H.S.P.A.

Repeated determinations of the wilting percentage on three Oahu soils indicate that plants as diverse botanically as sunflower and sugar cane deplete the soil moisture to essentially the same degree of dryness before the plants exhibit signs of distress because of inadequate moisture. (Table II.)

DISTRIBUTION OF SOIL MO

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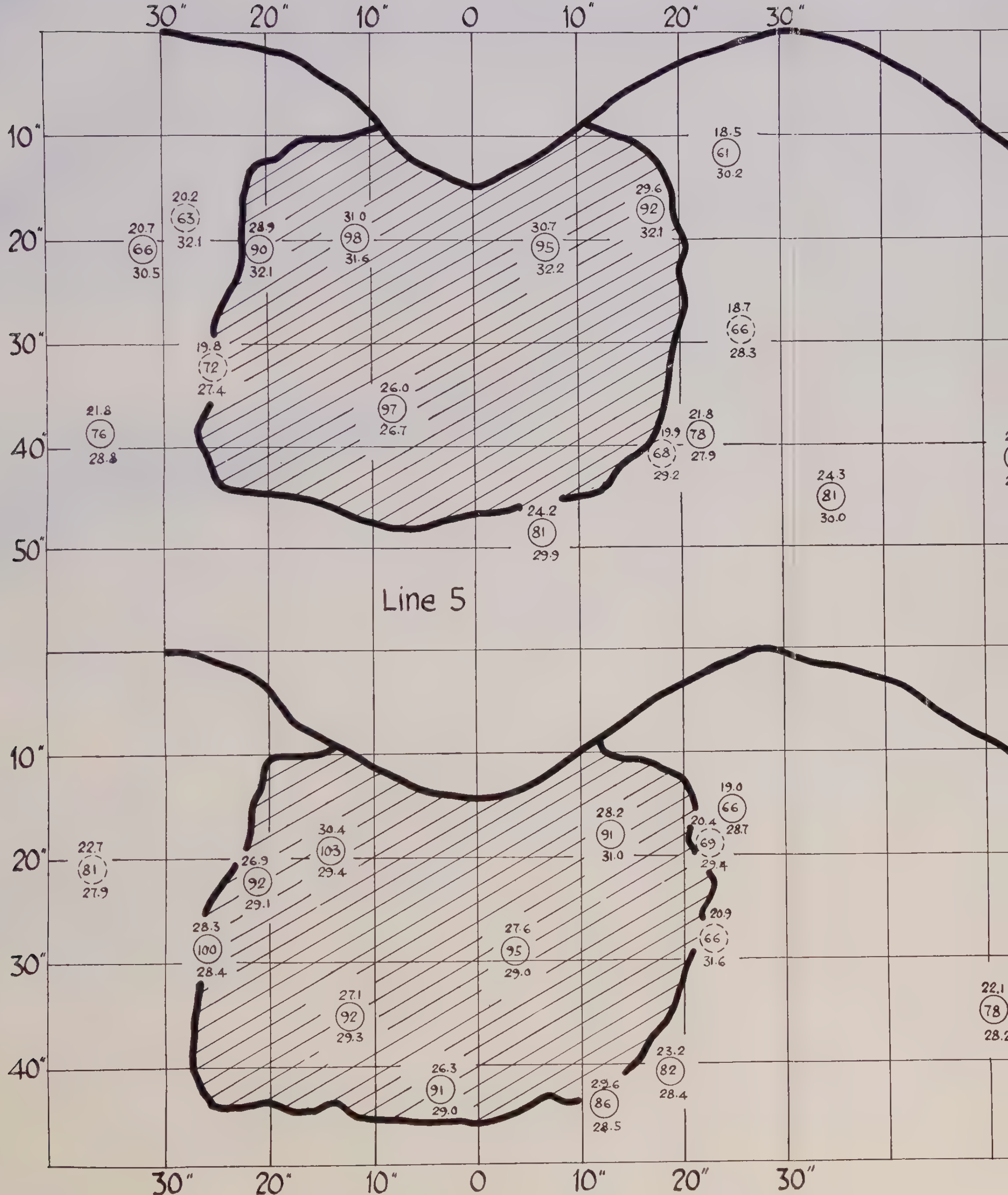
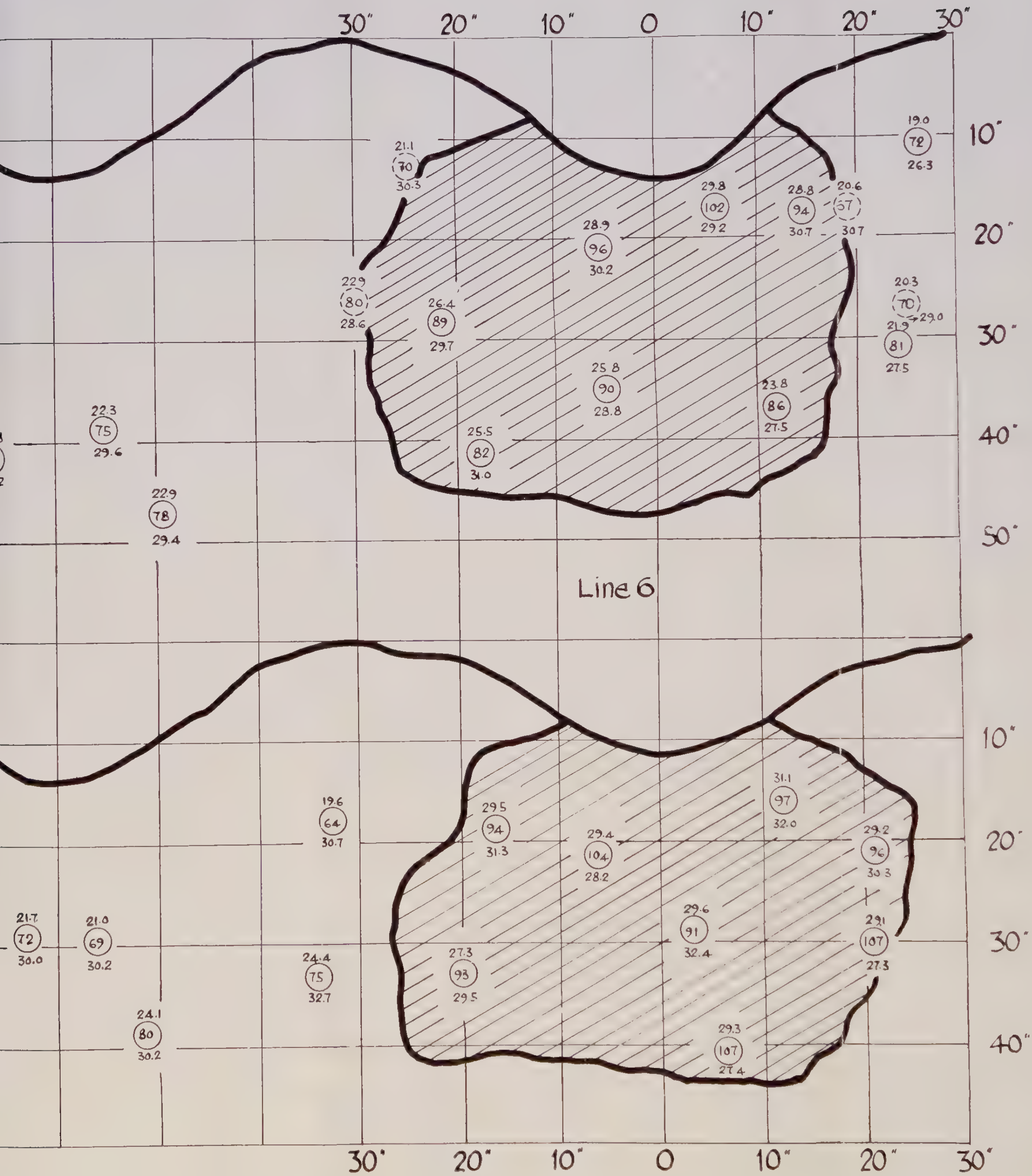


Fig. 3. Distribution of soil moisture

Circles represent position of soil mois
Dotted circles represent position of sa
Figure above circle—total percentage
Figure below circle—average of dupli
Figure in circle—"relative wetness"
Irrigation application of 2.00 acre-inc

STURE UNDER CONTOUR IRRIGATION

o Substation



nder contour irrigation—Waipio substation.

e samples.

ples for capillary movement.

il moisture.

ce moisture-equivalent determinations.

total moisture × 100 ÷ moisture equivalent.

per acre.

DISTRIBUTION OF SOIL MOISTURE UNDER

Waimanalo Sugar Co. Field

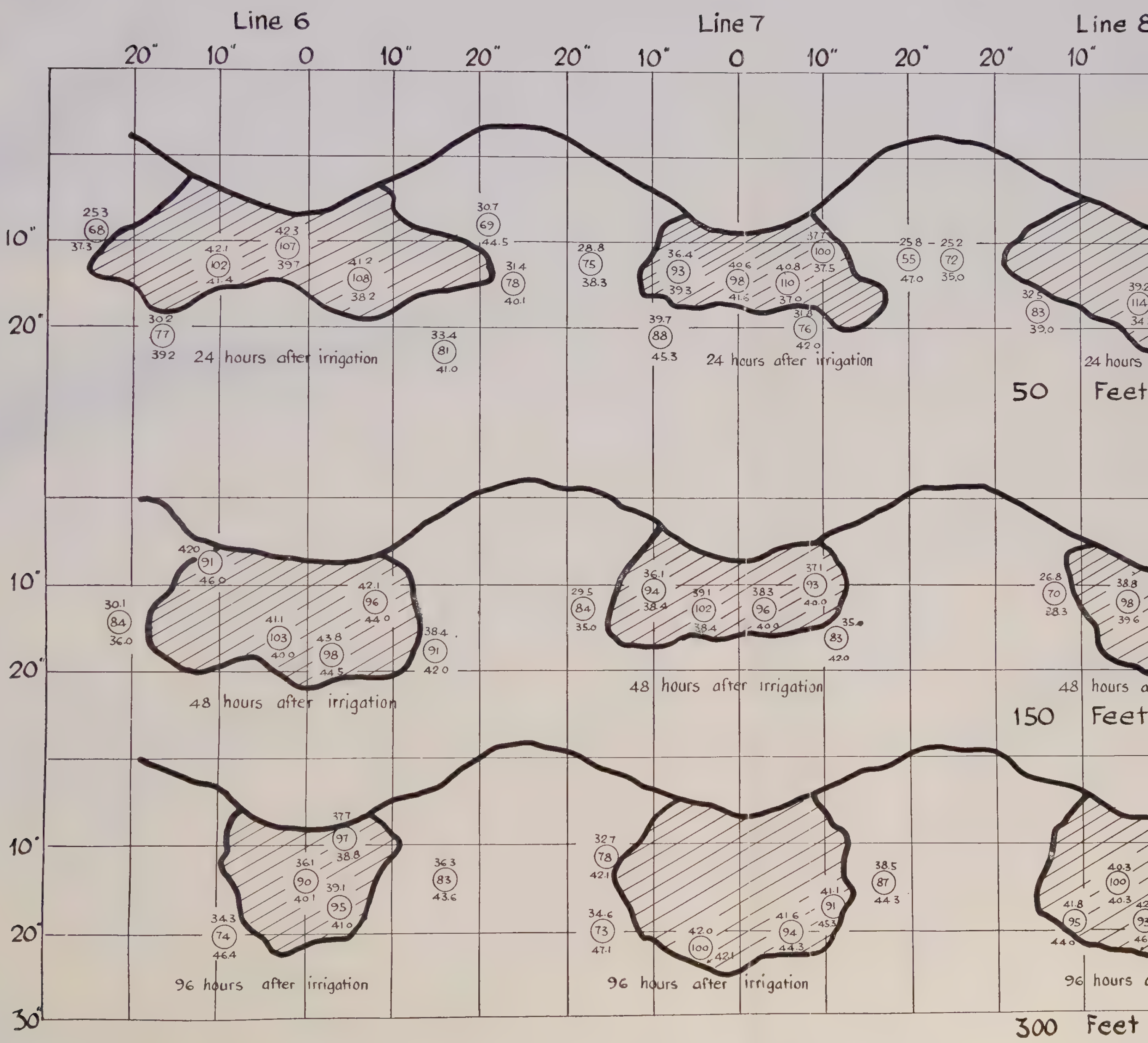


Fig. 4. Distribution of soil moisture under long-l

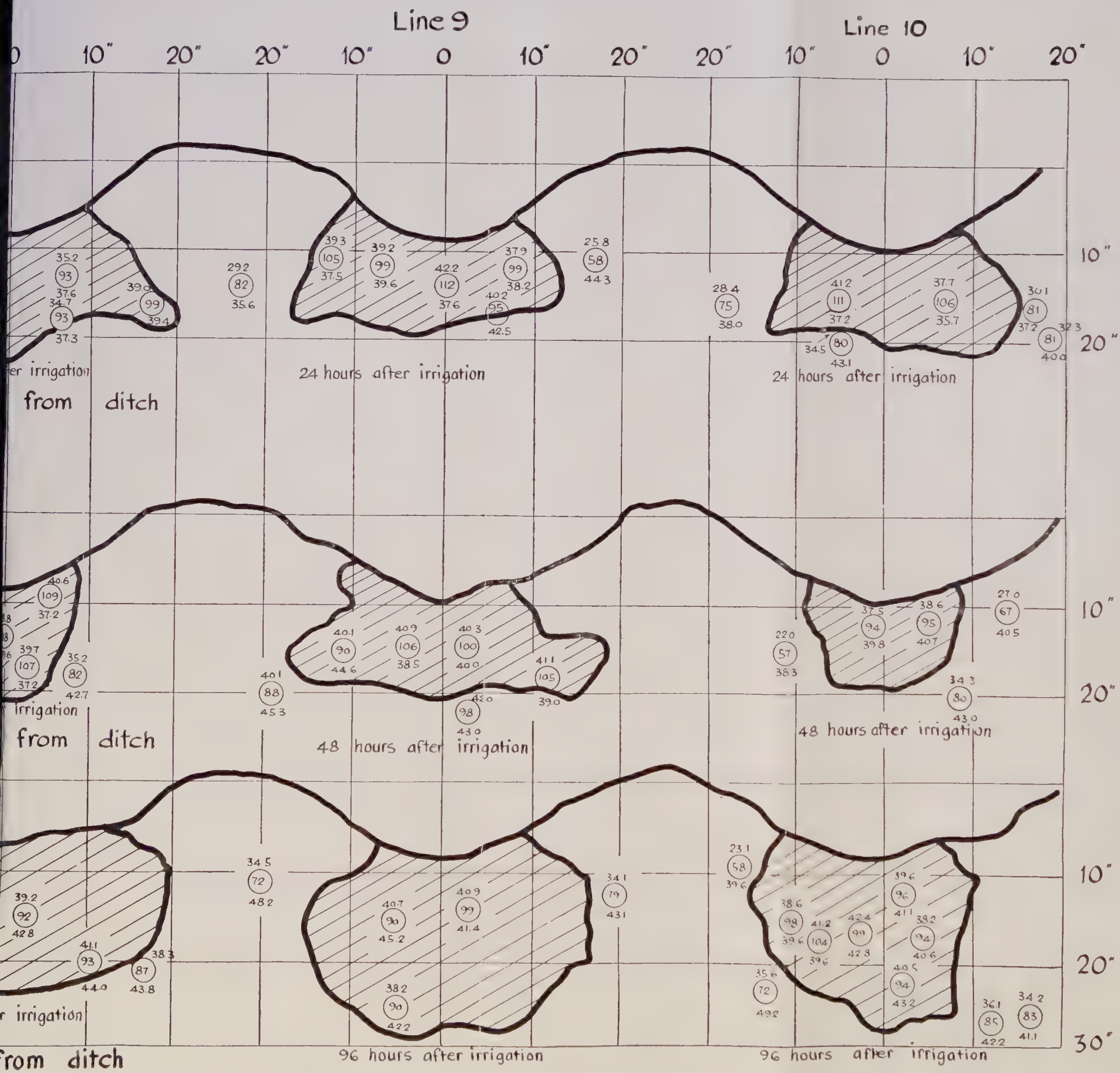
Circles represent position of soil moisture samples

Figure above circle—total percentage soil moistur

Figure below circle—average of duplicate moistur

Figure in circle—"relative wetness" or total moi

LONG LINE IRRIGATION



irrigation—Waimanalo Sugar Company, Field 11.

quivalent determinations.
re × 100 ÷ moisture equivalent.

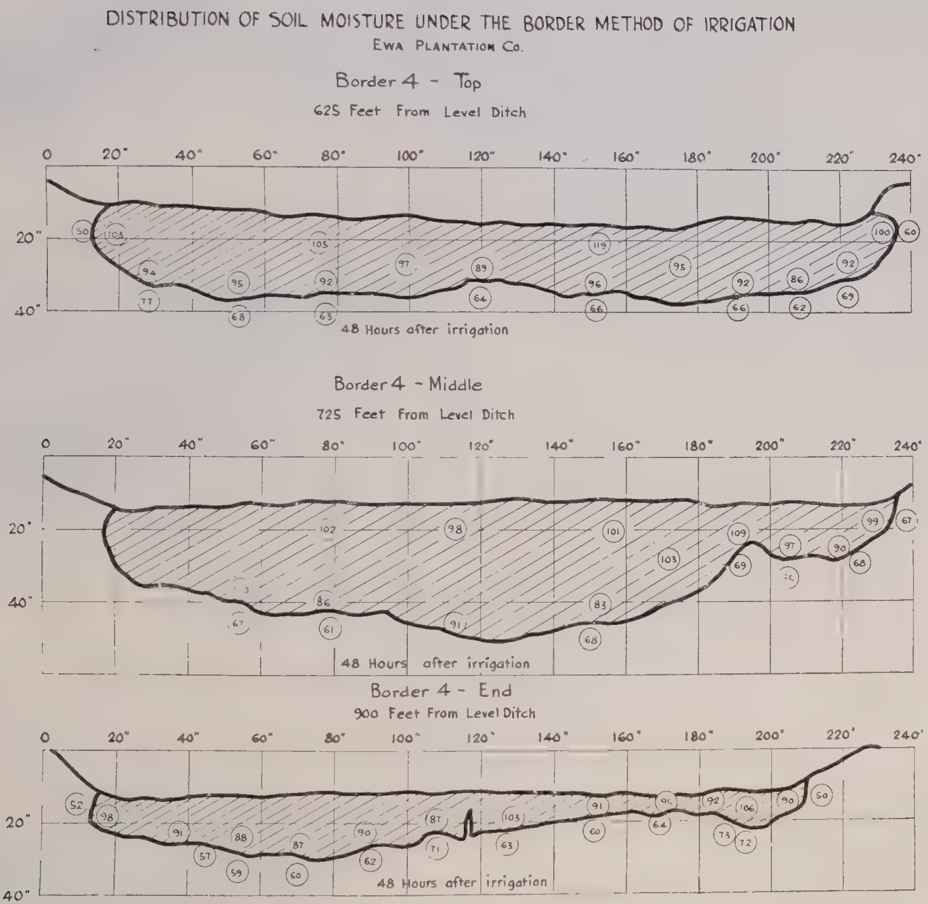


Fig. 5. Distribution of soil moisture under the border method of irrigation. Figures in circles refer to the "relative wetness" of the soil, or total per cent moisture × 100 divided by the moisture equivalent.

TABLE II

RELATION OF SOIL MOISTURE CONTENT AT PERMANENT WILTING OF SUNFLOWER PLANTS AND OF COMPLETE GROWTH CESSATION OF SUGAR CANE

		Soil Moisture Content at Permanent Wilting			
Soil Series	Soil Depth	Sunflower	No. of Determinations	Sugar Cane	No. of Determinations
Oahu 3-A	1	27.1±0.10	25	26.4±0.12	20
	2	25.5±0.15	17	25.3±0.07	20
	3	24.4±0.07	19	24.3±0.17	15
	4	24.6±0.08	20	25.4±0.18	16
	5	24.6±0.05	18	24.7±0.11	13
	6	24.6±0.08	21	24.6±0.08	21
	Average	25.2±0.07	120	25.2±0.07	120
Oahu 53	1	25.7±0.15	24	27.0±0.08	19
	2	26.1±0.06	19	25.9±0.10	22
	3	24.0±0.06	17	25.5±0.11	24
	4	24.3±0.05	18	25.8±0.09	15
	5	26.6±0.05	18	26.9±0.06	26
	6	26.5±0.09	17	27.0±0.05	18
	Average	25.6±0.07	113	26.4±0.05	124
Oahu 38	1	21.9±0.07	35	23.9±0.08	43
	2	21.3±0.07	34	22.9±0.08	32
	3	21.1±0.06	38	23.4±0.09	43
	4	25.0±0.07	36	25.7±0.07	36
	5	24.9±0.05	36	25.7±0.06	38
	6	25.1±0.06	37	25.9±0.11	27
	Average	23.3±0.08	213	24.5±0.06	219

The wilting percentages of other Hawaiian soils were determined with sugar cane as the indicator plant and with complete cessation of measured growth as the criterion of the critical lower limit of available soil moisture. The results of 952 observations on 45 soil series, showing consistent trends with acceptable probable errors in each trial, are given in Table III.

TABLE III

SOIL MOISTURE CONTENT AT PERMANENT GROWTH CESSATION OF SUGAR CANE IN VARIOUS HAWAIIAN PLANTATION SOILS

Soil Series	Depth	No. of Determinations	Permanent Wilting Percentage: Per Cent Soil Moisture	Probable Error: Single Observation	Probable Error: Mean	Moisture Equivalent	RATIO M.E./W.P.
Oahu 3A	1	20	26.4	±0.54	±0.12	34.9	1.32
	2	20	25.3	±0.31	±0.07	32.1	1.26
	3	15	24.3	±0.66	±0.17	28.4	1.17
	4	16	25.4	±0.72	±0.18	29.8	1.17
	5	13	24.7	±0.40	±0.11	30.3	1.23
	6	21	24.6	±0.37	±0.08	28.0	1.14
	Average	120	25.2	...	...	30.6	1.21
Oahu 53	1	19	27.0	±0.35	±0.08	34.6	1.28
	2	22	25.9	±0.47	±0.10	31.5	1.22
	3	24	25.5	±0.54	±0.11	29.4	1.15
	4	15	25.8	±0.35	±0.09	30.2	1.17
	5	26	26.9	±0.30	±0.06	28.7	1.10
	6	18	27.0	±0.21	±0.05	31.8	1.18
	Average	124	26.4	...	...	31.2	1.18
Oahu 38	1	43	23.9	±0.52	±0.08	31.5	1.32
	2	32	22.9	±0.45	±0.08	29.6	1.29
	3	43	23.4	±0.59	±0.09	29.0	1.24
	4	36	25.7	±0.36	±0.06	31.1	1.21
	5	38	25.7	±0.37	±0.06	31.4	1.22
	6	27	25.9	±0.67	±0.11	30.8	1.19
	Average	219	24.5	...	...	30.8	1.26
Ewa "A"	1	18	22.4	±0.60	±0.14	25.8	1.15
	2	9	22.6	±0.34	±0.11	25.3	1.12
	3	43	21.5	±0.78	±0.12	24.6	1.14
	4	32	21.3	±0.40	±0.07	25.8	1.21
	5	30	17.3	±0.37	±0.06	26.8	1.55
	Average	132	20.7	...	...	25.7	1.24
Ewa 20A	1	44	24.3	±0.77	±0.11	32.1	1.32
	2	33	23.3	±0.58	±0.10	29.0	1.24
	Average	77	23.9	...	...	30.5	1.28
Ewa 26B	1	23	26.9	±0.81	±0.17	36.1	1.34
	2	28	27.6	±0.93	±0.18	36.3	1.31
	3 (Coral)	16	26.7	±0.59	±0.15	27.1	1.01
Ewa 22C	1	29	26.3	±0.90	±0.17	35.1	1.33
Waimanalo 18	1	16	32.9	±0.40	±0.10	46.1	1.40
	2	11	37.9	±0.45	±0.14	51.5	1.36
	3	8	38.7	±0.33	±0.11	51.2	1.32
	4	7	38.5	±0.98	±0.37	50.4	1.31
	5	4	37.4	±0.47	±0.23	50.3	1.34
	6	3	37.1	±0.94	±0.54	49.6	1.34
	Average	49	36.4	...	...	49.8	1.37
Waimanalo 13	1	17	32.1	±0.59	±0.14	45.5	1.42
	2	5	41.8	±0.99	±0.44	47.9	1.14
	3	2	36.6	±0.24	±0.17	50.7	1.38
Pioneer E2	1	33	24.6	±0.52	±0.09	30.8	1.25
	2	16	24.7	±0.58	±0.14	30.0	1.21
	3	11	23.5	±0.77	±0.23	31.0	1.32
	4	3	26.0	±0.27	±0.15	32.7	1.26
	5	8	27.9	±0.21	±0.07	36.5	1.31
	6	18	28.2	±0.88	±0.21	34.8	1.23
	Average	89	25.6	...	...	32.6	1.27
Pioneer O2	1	22	18.5	±0.67	±0.14	22.9	1.24

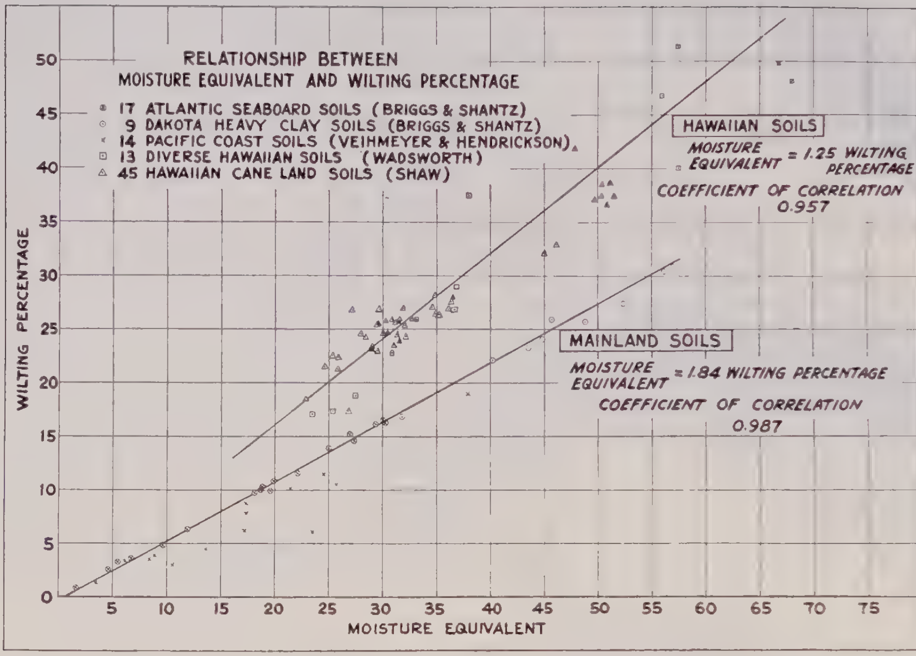


Fig. 6. Relationship between moisture equivalent and wilting percentage.

The relationship between the wilting percentage and the moisture equivalent is illustrated in Fig. 6. Here are shown the results of the original work by Briggs & Shantz as reported to the American Society of Agronomy in 1911, and the exceptions noted by Veihmeyer and Hendrickson, in *Plant Physiology* for 1928, to the constant ratio of 1.84 between the two soil moisture constants. On the same scale are shown the results of the 45 series of determinations on Hawaiian soils reported in this paper, and those reported by Wadsworth in 1933 on diverse Hawaiian soils from the islands of Maui and Hawaii.

Although there can be no doubt of the general relationship and trend between the moisture equivalent and the wilting percentage of any soil, the ratio between these two factors on Hawaiian soils is far different than that of most Mainland soils. The difference may be due to the character and quantity of the colloidal material of local soils, or to the difficulties in preparing field samples for the determination of both moisture equivalent and wilting percentage.

A ratio of 1.25 between moisture equivalent and wilting percentage appears to give a reasonable approximation of the lower limit of available soil moisture for most Hawaiian soils studied, particularly for the red residual soil which forms a major portion of the irrigated sugar lands of Hawaii. However, there are enough exceptions and departures from the general ratio to make the use of the moisture equivalent for this purpose advisable only in first approximations of the wilting percentage value. For precise estimates of this critical soil moisture constant, actual determinations should be made by measurement in the field, as described in a subsequent chapter.

"Tank" Studies: The next phase in the Waipio investigations of 1928-1932 was a study by Prof. Wadsworth and the writer on the growth and water relations of sugar cane grown to maturity in large tanks having a capacity of over one ton of soil. The specifications of the tanks and the general procedure were copied directly from the original work of Veihmeyer on orchard trees in California, with such modifications as were necessary in view of the different nature of the crop grown.

Two crops of eighteen months each were grown in the tanks under carefully controlled moisture conditions. In general, the results substantiated the major premises of the modern conception of plant and water relations. The cane grew at a constant rate, affected only by seasonal changes, after irrigation water was applied. When the soil moisture percentage reached a critical value, 23.3 per cent in this particular soil, the growth rate was greatly affected and elongation soon ceased entirely. The same disturbance of growth occurred at precisely the same soil moisture content throughout the life of the cane during both crops, being unaffected by season of year or age of cane. Considerable quantities of water were transpired by the cane even when the soil moisture was too low to permit active plant growth. Soon after irrigation water was applied to the soil, the cane resumed essentially the same rate of growth which it had enjoyed prior to the period of water privation. In a few extreme cases, however, when water was withheld for long periods of time the rapidity of recovery and the resulting growth rate were detrimentally affected for the remainder of the crop.

Field Studies and Observations: Observation and experimentation in the field under normal growing conditions demonstrated that a reliable index of the rate of crop growth could be obtained by the measurement of 20 stalks of cane in close proximity. The typical straight-line curve of cane growth for some time after irrigation, and the obvious break in the curve when the soil moisture was at the wilting percentage indicated that soil moisture and cane growth observations might be used as a guide in predicting the irrigation requirements of commercial fields of sugar cane.

Modern Conception of Plant and Water Relations in Hawaiian Soils:

The substantiation and modification of the modern conception of plant and water relations as they apply to most Hawaiian soils may be summarized as follows:

1. Studies in Hawaii as early as 1896 recognized the variation in the power of Hawaiian soils to hold moisture. Many local investigators have noted that soils can hold only a definite amount of water and that additional water was wasted by deep penetration.

2. The limited movement of water from moist to dry soil by capillarity and the limited extent of lateral moisture movement in the soil was early recognized by investigators in Hawaii.

3. Experiments conducted from 1916 to 1926 on plantations of the Territory approached the conception of a wilting percentage or lower limit of available soil moisture. In general, however, the wilting percentage was apparently considered as a function of the cane plant rather than of the soil, subject to seasonal variation and to the age and variety of the cane.

4. Studies by the Experiment Station, H.S.P.A., since 1928 have attempted to determine basic relationships between the cane plant, plantation cane land soils, and irrigation water with the view of obtaining methods by which commercial irrigation could be guided more economically and skillfully.

5. Investigations conducted in the laboratory, in pot tests, in large tanks, and in the field have established certain fundamental relationships which may well be considered and used in commercial irrigation:

a. Cane growth is independent of the soil moisture content for some time after irrigation, the growth rate being influenced only by season, age of cane, and by cultural operations other than irrigation.

b. Cane growth is severely affected, and may cease entirely, when the soil moisture content reaches a critical value which is dependent upon the physical nature of the soil rather than upon the type of plant or the season.

c. The cane plant does not exhibit external symptoms of wilt for several days after the critical limit of available soil moisture for growth has been reached. The appearance of the plant or of the surface of the soil are not safe standards on which to base the need for irrigation water.

d. The normal rate of cane growth is resumed quickly after irrigation water is applied unless the period of inadequate soil moisture is sufficient to damage the physical structure of the plant.

e. The cane plant continues to transpire considerable quantities of water even when the soil moisture content is too low to promote active growth.

6. In an attempt to develop a single-value soil constant which could be used to classify soils on the basis of their moisture-holding characteristics, a simple laboratory determination called the moisture equivalent was examined critically:

a. The moisture equivalent appears to be the best available method for the rapid classification of the physical nature of Hawaiian soils.

b. The maximum field capacity is equal to 1.1 times the value of the moisture equivalent on practically all soils examined.

c. A high correlation was found between the moisture equivalent and the permanent wilting percentage, or lower limit of available soil moisture. The moisture equivalent of a soil divided by 1.25 is roughly equal to the wilting percentage of that soil. However, enough exceptions and departures from this generality exist to warrant caution in the use of the moisture equivalent for precise determinations of the lower limit of soil water available for cane growth.

THE WAIALUA IRRIGATION INVESTIGATIONS

By J. A. Swezey

Five years of basic research by the Experiment Station, supported by independent studies of many individual plantations, indicated that fundamental relationships between Hawaiian soils, irrigation water, and the sugar cane plant substantiated in general the results of similar investigations in Europe and Mainland United States. The research demonstrated that soil moisture and cane growth measure-

ments might prove of value in obtaining more efficient irrigation on plantation field areas.

Reasons for the Investigations

The next logical development in the series of investigations was in the application of these scientific tools for irrigation guidance to commercial field practice. This opportunity arose during the latter part of 1932 when Mr. Shaw transferred from the Experiment Station to the Waialua Agricultural Co., Ltd. He was requested by the plantation management to outline a program which would lead toward better control and more efficient use of the plantation water supply. His suggestions included a coordinated plan of water measurement and administration, the classification of plantation soils on the basis of their moisture-holding characteristics, and the application of soil moisture and cane growth measurements to commercial field areas in an effort to obtain more information on the relation of soil water to crop production and to develop a practicable means of applying these data to routine irrigation control.

Purpose of the Investigations

The Experiment Station was sufficiently interested in the possibilities of this form of investigation in relation to the irrigated plantations of the Territory to suggest a cooperative project between the Experiment Station and the plantation. The Director of the Experiment Station outlined the purpose of the project in a letter to the Experiment Station Committee as ". . . a study of means to determine more accurately the interval permissible between irrigations under the several variables of (a) age of crop on the land, (b) climatic conditions for the period in question, and (c) type of soil, etc. At the present time the decision of when and where to place water over a large area is based to a very considerable extent upon human judgment. If we had the knowledge as to where water, when not abundant, could be used most effectively in point of its sugar-producing value, the profits on a large plantation could very probably be increased by hundreds of thousands of dollars in the course of a year. . . . The Waialua plan is a logical sequel to the other work, and it aims to construct a bond leading from our present scientific knowledge to the development of precision in irrigation practice."

The cooperative project was approved, and with Prof. Wadsworth in consultation and the writer in residence on the plantation, the investigations were started in the early spring of 1934. This report deals with the methods developed in classifying the plantation soils on the basis of the moisture equivalent, with a detailed description of methods and results of field studies on the relation of water to crop production from commercial cane areas, and with the application of the procedure developed in the field to plantation irrigation practice.

Classification of Plantation Soils

Laboratory Procedure:

The first phase of the Waialua investigations was the classification of soil types by means of a moisture equivalent survey covering the entire plantation. Since the moisture equivalent served as the basis of classification, the laboratory procedure employed in determining this soil characteristic will be described briefly:

1. The soil sample is air-dried for 24 hours.
2. The soil is then sifted through a 2.0-millimeter screen.
3. Screened soil equivalent to about 30 grams on an oven-dry basis is placed in each of four centrifuge cups.
4. The cups, containing soil, are immersed in distilled water for 24 hours. during which the soil becomes saturated.
5. The cups are then placed in a centrifuge for 30 minutes at 2,440 revolutions per minute, which develops a force equivalent to 1,000 times the force of gravity.
6. The residual moisture contents (oven-dry basis) of the soils in the four cups are averaged. The average per cent moisture is reported as the moisture equivalent of the sample.

Field Procedure:

The field procedure used in making the moisture equivalent survey was conducted as follows:

As soon as possible after the harvesting of each field, two permanent points or a permanent line, such as a railroad, were located and identified on the map of the field, to serve as a base line. From this base line a system of coordinates at 300-foot intervals was developed and drawn on the field map. Each coordinate intersection within the field boundaries was assigned a number. With transit and chain, these points or stations were located in the field, a flag being planted at each station. The base line was referred by horizontal angle to some third point external from its extremities. The mill stack was usually found to be a convenient reference point. This triangulation made it possible to relocate any individual station in the future.

At each station a 2-inch boring was made to a depth of 2 feet and two samples obtained. Each sample was sufficient to fill a one-pound can, one being of all soil to a depth of one foot, the second being from the 1- to 2-foot depth. Field notes on general topography and on soil color and texture were recorded for each sampling station. By this method of sampling, information was acquired for each two acres over the entire area of the plantation.

Results of the Completed Survey:

All soil samples were sent to the Waipio soil laboratory of the Experiment Station, where they were analyzed for moisture equivalent values by the method described above. The data were classified according to the table appearing immediately below:

TABLE IV

CLASSIFICATION OF PLANTATION SOILS BY MOISTURE EQUIVALENT VALUES

Moisture Equivalent Class Per Cent	Predicted Value of— Maximum Field Capacity Per Cent	Predicted Value of— Wilting Percentage Per Cent	Predicted Range of Available Soil Moisture Per Cent
25.0 and less	27.5 and less	21.0 and less	6.5 and less
25.0 to 30.0	27.5 to 33.0	21.0 to 25.0	6.5 to 8.0
30.0 to 32.5	33.0 to 36.0	25.0 to 27.0	8.0 to 9.0
32.5 to 35.0	36.0 to 38.5	27.0 to 29.0	9.0 to 9.5
35.0 to 40.0	38.5 to 44.0	29.0 to 33.5	9.5 to 10.5
40.0 to 45.0	44.0 to 50.0	33.5 to 37.5	10.5 to 12.5
45.0 and over	50.0 and over	37.5 and over	12.5 and over

Predicted maximum field capacities and wilting percentages were computed by the following formulae:

Maximum field capacity $\doteq$ 1.1 $\times$ moisture equivalent.

Wilting percentage $=$ moisture equivalent $\div$ 1.2.

In the second equation the factor 1.2 is used instead of 1.25 as given previously in this report for the following reasons:

(a) Previous determinations had shown the factor 1.2 to hold for most Oahu residual soils.

(b) Since moisture equivalent was to be used as a general guide, a factor significant to tenths instead of hundredths was sufficiently accurate.

A color symbol was assigned to each moisture equivalent class, and the data for each station were plotted on the field map with color. This initial plotting was later transferred, again with color, to the map of the plantation.

The completed survey has contributed valuable basic information on the variation of soil types over the plantation area. It has demonstrated that the area of the plantation may be divided into definite soil groups determined by their parent material and degree of weathering, each of which has definite characteristics of moisture retention and physical structure. Very briefly, these soil groups may be defined as follows:

Group I—The Mountain Belt extends from the 550-foot contour to the upper limits of the plantation. It is characterized by soils of high moisture-holding capacity, with moisture equivalent values from 35 to 45 per cent, and available soil moisture from 10 to 12 per cent. The soil is deep and uniform as to depth and area.

Group II—The Middle Belt extends from the 300-foot contour to the 550-foot contour. It is characterized by soils of good moisture-holding capacity, with moisture equivalent values from 30 to 35 per cent, and available soil moisture from 8 to 10 per cent. The soil is fairly deep and uniform on plateaus, with rather shallow topsoil and low retentiveness on palis and ridges.

Group III—The Lowland Belt extends from the 100-foot to the 300-foot contours. It is characterized by soils of low moisture-holding capacity, with moisture

equivalent values from 25 to 35 per cent, and available soil moisture from 6.5 to 9.0 per cent. There is evidence of erosion and shallow topsoil throughout, with very low moisture retentiveness on ridges and palis. This belt is marked by heavy rock deposits and diverse soil-type distribution, especially near the older Waianae Range. Apparently it is the upper edge of an alluvial fan.

Group IV—The Coastal Plain extends from sea level to the 100-foot contour. It is characterized by soils of high moisture-holding capacity, with moisture equivalent values from 35 to 45 per cent and greater, and available soil moisture from 10 to 14 per cent. The soils are chiefly alluvial deposits from the uplands and marine deposits from old high-level seas. The soils are of variable depth and uniformity, often broken by old coral beds.

Group V—The Beach Belt is a limited and broken area close to sea level. It is characterized by soils of very low moisture-holding capacity, with moisture equivalent values 25 per cent or less, and available soil moisture 6.5 per cent or less. This belt is chiefly old beach lines and coral outcrops.

It should be understood that this soil classification is not necessarily a reflection of the productivity or fertility of the areas described, but pictures rather sensitively the physical and particularly the moisture characteristics and limitations of the soil. Other things being equal, a soil in Group III might well produce as much or more sugar per acre as a soil in Group I or II, but it would require more frequent applications of water to maintain the same rate of growth.

Field Studies of Plant and Water Relations

Location of Observation Stations:

The object of the next phase of the Waialua investigations was an attempt to learn more precisely, under actual commercial field conditions, the effect of weather variations, soil type, age of cane, and similar factors on the interval permissible between irrigation applications, if uninterrupted cane growth was to be maintained.

The field studies at Waialua of the basic relationships were not experimental in the sense that there was any comparison of treatments. The investigators did not aim to control any factors affecting the development of the 1936 crop, but to observe and record all natural conditions and phenomena attendant upon the development of the crop. It was intended that analysis of these records should form a basis for a future control program.

Six fields for observation were selected in 1934 at key positions, extending from one extremity to the other of the plantation and from sea level to 750 feet elevation, embracing diverse combinations of soil type, elevation, exposure, and cane age, and each representing a considerable area in its district.

Information relative to the locations of these six fields is tabulated below:

Field	Elev. Ft.	Crop Started	Soil Group	Geographical Location	General Comments
Waimea 3	355-410	3/5/34 (Ratoon field)	I	North end of plantation. Rainy region. A mauka field.	Exposed to tradewind on northeast side. Small gulley in northern part of field. Deep ravine in southern part. Water supply at times limited.
Kawailoa 3	180-240	3/22/34 (Plant field)	III	North-central portion of plantation. Region of medium rainfall. A makai or lower middle belt field.	Somewhat shielded by camp on mauka side. South side ends on edge of deep gulch. Irrigation by pump water. Flat, gently sloping surface.
Opaeula 13	590-690	6/14/34 (Ratoon field)	I	East-central portion of plantation. Extreme mauka field.	Exposed on mauka side to northeast tradewind. Flat, medium-sloping surface. Irrigation by mountain water, fairly reliable supply.
Helemano 2A	60-190	8/7/34 (Ratoon field)	III	Central part of plantation. A makai field on foot of ridge.	Somewhat shielded from northeast winds by end-sloping of ridge. Surface terraced, with steep pitches in upper portion. Irrigation by pump water.
Mill 2	15-20	4/30/34 (Ratoon field)	IV	West-central part of plantation. Extreme makai field.	Practically level field with slight depression in middle. Irrigation by pump and mill water.
Gay 7	150-250	4/11/34 (Ratoon field)	III	Western portion of plantation. A mauka field for this part of plantation.	Shielded from wind on mauka side, makai side somewhat exposed. Medium, flat slope. Pali in makai side of field. Irrigation by somewhat limited supply of water.

(H 109 cane under contour method of irrigation in all fields)

General Description and Equipment of Observation Stations:

In each of these fields, a location was selected which was considered by the Division and Irrigation Overseers to be an average one relative to water requirement, soil type, and yield ability as based on cane stands of previous crops. It was required that this localized area be on a medium, well-drained slope, with furrows in good condition. Within this area, a line of cane was selected which fulfilled the following specifications:

1. Shoots should be of about equal height.
2. Shoots were uniformly spaced from end to end of the line.
3. The line was 50 feet or more within the field boundary. This line of cane was termed the "Station line."

Detailed information on the average moisture equivalent of the vicinity was obtained by sampling at the locations shown in Fig. 7. Two samples were taken from

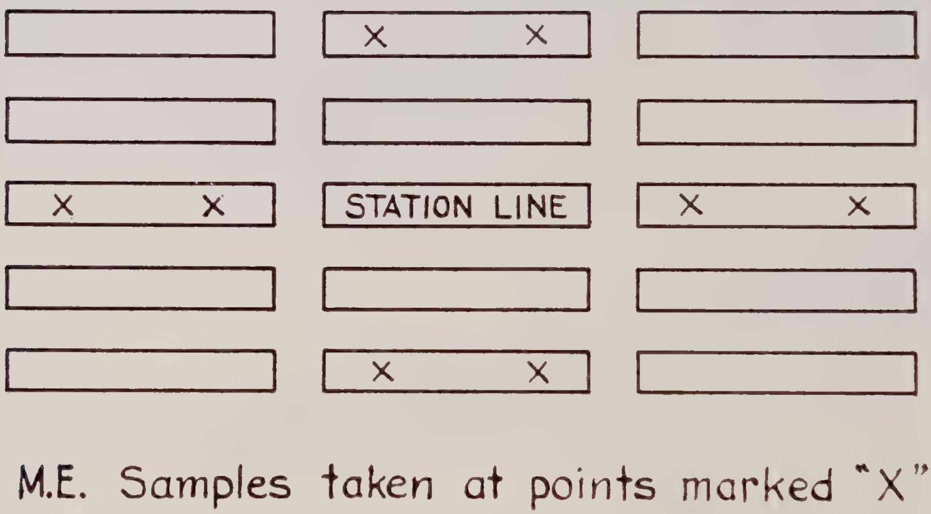


Fig. 7. Plan of vicinity surrounding cane growth and soil moisture observation station, showing location of borings for moisture-equivalent samples used in predicting limits of available soil moisture.

each boring: one from the first foot and one from the second foot. The average moisture equivalent thus obtained was used to predict the maximum field capacity and wilting percentage of the observation station.

On the edge of the field near each observation station the following weather instruments were installed: maximum and minimum thermometers (U. S. Weather Bureau type), and a rain gage. At the Waimea 3, Opaeula 13 and Mill 2 stations, an evaporation pan was also included in the equipment.

Substations were established at two other remotely separated points in each observation field. The selection of locations and of shoots was made in the same manner as for the main station of the field. At these substations only 10 stalks were tagged, and no samples were taken for moisture equivalent analysis.

Fig. 8. Typical weather station. Left to right: evaporation pan, rain gage, thermometer shelter. This is the source of weather data for comparison with growth and soil moisture data.

Observation Procedures:

At each of the main stations observations were made daily (except on Sundays and holidays) of the length of each of 20 stalks, soil moisture by sampling the vicinity of the station line, and weather. At the substations weekly observations were made of the lengths of 10 stalks, the purpose of the substations being to obtain a rough comparison of the rate of growth in various parts of the field.

Methods and technique employed in making these observations will be described in this section of the report.

General Procedure: Precautions were taken continually to avoid disturbing the normal condition of the cane. The observers entered and left each station by a different route as much as possible to prevent excessive packing of the soil. The ground was covered with trash to cushion the effects of walking and standing.

Weather Observations: Standard U. S. Weather Bureau procedure was employed in reading the weather instruments. The observers recorded their personal estimate of the character of the sky ceiling, as well as of direction and approximate strength of wind, and presence of dew.

Technique of Soil Moisture Observations: A description of the technique of observation follows; with, first, a discussion of the soil moisture sampling and determination.

To insure obtaining reliable data in which confidence could be placed, precise specifications were adopted for the procedure of soil moisture observation. These specifications required that exactly the same procedure be followed for each subsequent observation, as a means of reducing accidental errors. Controllable errors were eliminated by proper procedure.

Sampling Methods Used in the Field: A moisture observation was made by boring a hole one or two cane lines mauka of the "station line," and another hole one or two lines makai. This is shown in Fig. 9. The holes for each successive obser-

vation were bored about 8 inches from the last previous observation holes. Thus about three months might elapse before the sampler covered the route shown in Sketch B of Fig. 9. All holes were bored in the bottom of the furrow (Sketch A, Fig. 9). The depth of boring was two feet. One sample was obtained from the first foot and one from the second foot of each hole. Per cent moisture was deter-

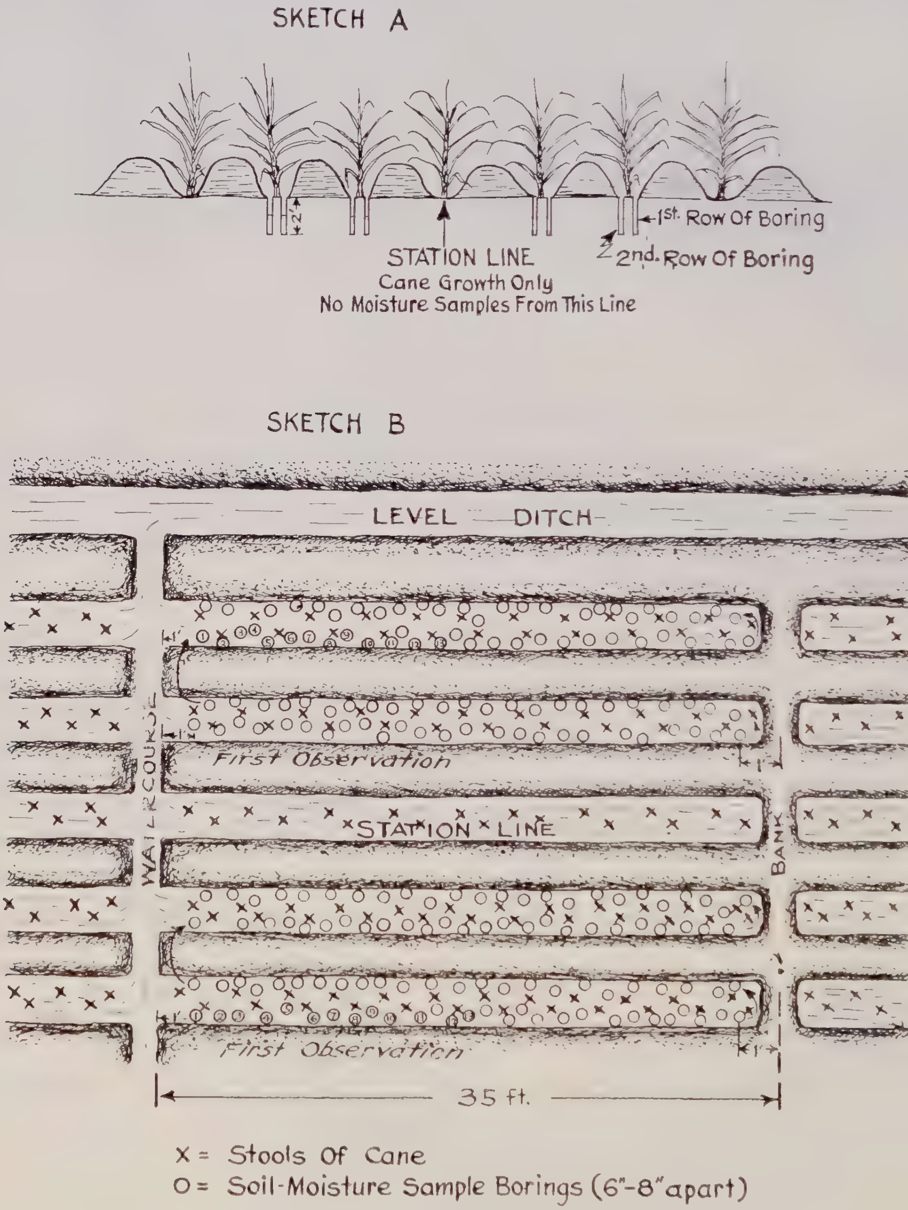


Fig. 9. Sketch A—Location of soil moisture sample borings relative to furrows and cane stools.

Sketch B—Location of soil moisture sample borings relative to measured-stalk line, also showing route followed from day to day by sampler.

mined for each of the four samples constituting the observation. The average per cent moisture was reported for plotting on the graphical records for the Station. The four individual determinations of moisture afforded an indication of the general vertical and lateral distribution of moisture in the area surrounding the line of cane in which stalk elongation was being measured.

Special care was exercised in boring all sample holes. In all cases under normal conditions the first (or top) one to two inches of soil were scraped away from the

Fig. 10. Moisture sampling. One man can take sample alone, but in big cane, time is saved by working in pairs.

point at which the hole was to be bored. This was done to prevent loose soil, which was subject to drying by evaporation or wetting from light dewfall, from dropping into the hole and thus being mixed with the sample. In removing the auger from the hole, care was taken to avoid scraping the walls of the hole, thus preventing contamination of a sample from the bottom of the hole with soil from the upper horizon. After rainfall of up to one-half inch, approximately, which would penetrate only a few inches and therefore produce an average moisture determination somewhat misleading as to the actual moisture available to the cane, the top 4 to 6 inches of soil were discarded from each boring.

Each sample consisted of portions of soil taken from all parts of a well-mixed pile. The soil was placed loosely in an eight-ounce, airtight can. The unused remainder of each pile of soil was returned to the hole and tamped tight. This prevented seriously altering the condition of the field in the vicinity of the station. The soil and the cans containing soil were protected from exposure to the sun and wind. Can numbers were recorded as soon as the samples were placed in these containers. Can markings were renewed frequently to avoid illegibility. These precautions assisted in producing reliable results.

Laboratory Equipment and Procedure for Moisture Determination: The moisture content of the soil samples was determined in the laboratory by the following procedure:

For all moisture determinations made during these investigations, weighing was accomplished with a torsion balance, sensitive to 1/10 gram. Weights used were of the analytical type. The ovens for drying soil were provided with thermostatic temperature control.

All of the sample brought from the field in the sample can was used for the moisture determination. The usual amount of wet soil put through this determination was 100 to 130 grams. All sample cans were tared to equal weight with solder which facilitated weighing and simplified calculations, as the sample was weighed and dried in the sample can and the tare weight of the can was balanced by a counterweight. The can weights were checked from time to time and necessary adjustments made to maintain the tare. The samples were dried in the oven from 22 to 24 hours at 100° to 105° C. Per cent moisture was expressed on an oven-dry basis.

Very soon after commencement of observations in 1934, several tests were made to ascertain the advisability or necessity of incorporating certain other standards in the general technique. Results of these tests showed the following:

(a) The sample could be exposed to the air, by removing the lid from the sample can, for well over 5 minutes without any significant loss of moisture, due to the relatively large bulk of the sample. Thus, haste and error could be avoided, since only 1 or 2 minutes of exposure were required in obtaining the wet weight.

(b) It was an unnecessary waste of time to cool the samples in a desiccator, as is usually done in laboratory practice, before obtaining the dry weight.

(c) Constant dry weight could be obtained in 20 to 24 hours of drying. It was satisfactorily proven that 48 hours of drying was unnecessary. Other frequently repeated tests checked the uniformity of drying conditions throughout the oven.

Toward the end of the observations of the 1936 crop, plans were made for the practical application of the results of this investigation. The program involved a heavy schedule of daily observations with a correspondingly large number of moisture determinations. Furthermore, it was desired that the per cent moistures of each day's samples should be reported at 8:00 a. m. the following day. This meant that the time required for moisture determination must be materially reduced. Such a time reduction could be effected by decreasing the manual operations, as well as by shortening the time of drying.

Acceleration of the manual operations was obtained by purchasing a self-reading scale and by using shallow, rectangular trays for the drying of the soil. These trays were tared to equal weight, which was checked and adjusted each month. The scale is a self-reading type similar to the butcher's or delicatessen's but calibrated in grams and specially equipped with an extra-length counterpoise beam. The beam is designed so that the counterpoise can be set to back-weigh or tare in multiples of 50.0 grams. Less than 50.0 grams can be read on the indicator chart to an accuracy of 0.1 gram. The beam is fitted at its extremity with a special pan, hung on a ball bearing, on which the soil moisture tray is placed for weighing. (See Fig. 11.) Weighing of wet or dry soil is a very simple rapid procedure in which all calculations are eliminated by the use of a conversion table. The whole process of determining per cent moisture is described as follows:

The scale counterpoise is set at the proper point on the beam to balance the tare weight of the moisture tray. Exactly 100.0 grams of the wet sample are placed in

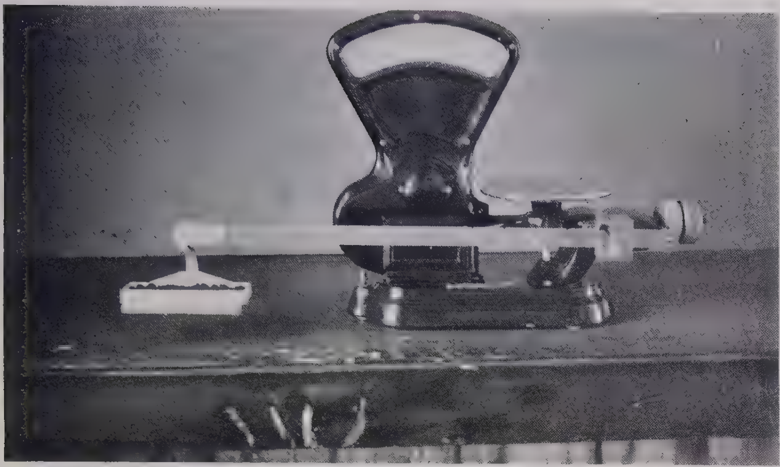


Fig. 11. Self-reading, specially designed scale used in laboratory determination of soil moisture developed during this investigation.

the tray, as checked by reading the indicator chart. When the wet weight of all samples is thus obtained, the trays are placed in the oven, eight on each shelf, and dried for 16 or more hours at 105° C. Dry weights are then obtained for each sample. These are the only weights the analyst is required to record. No calculations are necessary as the dry weights are changed to per cent moisture content by the conversion table, a portion of which appears below. As an example it is seen that a sample, having a dry weight of 24.3 grams, originally contained 34.6 per cent moisture.

CONVERSION TABLE FOR SOIL MOISTURE DETERMINATION

Scale Chart Reading (with dry soil on scale)	Per Cent Soil Moisture
24.6	34.0
24.5	34.2
24.4	34.4
24.3 ———————————	34.6
24.2	34.8
24.1	35.0
24.0	35.1

Appropriate tests were made to determine the 16 hours at 105° C. as being the correct time for drying with the new type of tray. Other tests indicated that the slightly greater number of samples in the oven did not impair the uniformity of drying conditions throughout the oven.

This new type of equipment developed for the extensive soil moisture program at Waialua plantation offers several desirable features. These are a slight increase possible in oven load, decrease in time required for drying, and a decrease in time for the manual operation of weighing. Several tests indicated that the manual operations with the new equipment require, conservatively, one hour and 12 minutes less for weighing 100 samples than did the original equipment used for the investigations. It is to be emphasized that both types of equipment are available and that both give equal accuracy of results.

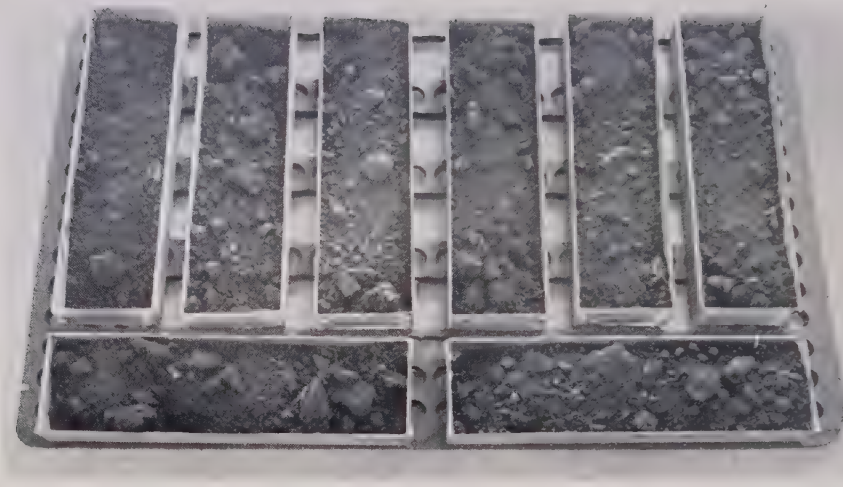


Fig. 12. New type of moisture trays as placed on oven shelf. Procedure developed during this investigation.

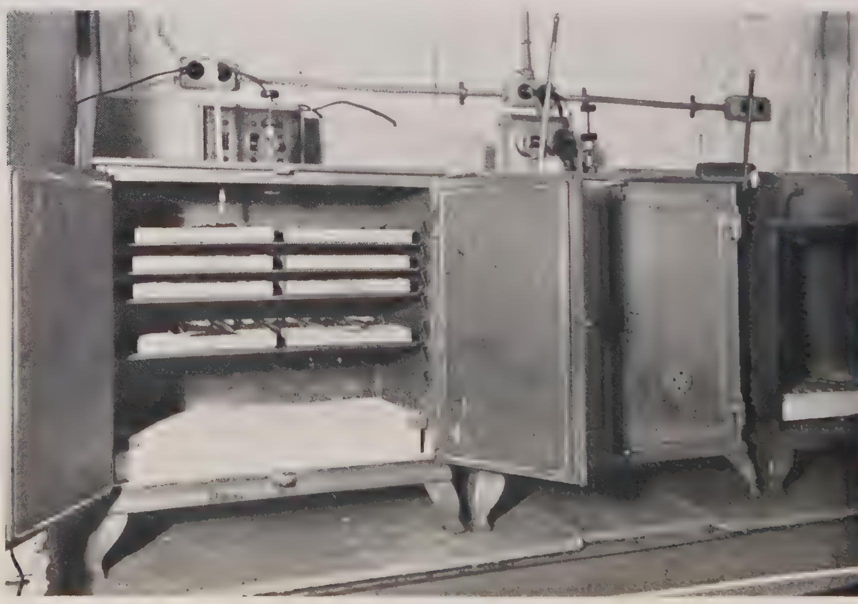


Fig. 13. Oven loaded with 6 shelves, each holding 8 trays. Ready to start 16 hours of drying at 105° C. according to new method.

Technique of Cane Measurement: Simultaneously with the moisture sampling, observations were made of the length of each of the 20 stalks at the station, and the average length obtained. The method of selecting these stalks has been mentioned, and it was stated that each was permanently identified by a number tag. At each successive observation the same stalks were measured, and precise and perfectly comparable records of stalk elongation were obtained. If an entirely new set of stalks had been measured at each visit, the average lengths would have fluctuated

from day to day and no continuity would have been possible in a curve of average lengths plotted against elapsed time.

The method of measuring the length of a single stalk is more or less a standard procedure, but it is advisable at this point to describe the process as applied in the Waialua investigations.

The length of each stalk was observed by the following method:

A large (10-penny) nail was driven into the ground at the base of each stalk shoot, the head of the nail being left about one-half inch above ground surface, so as to be clear of later-deposited silt. These nails served for some months as "zero" datum points.

A steel tape, one meter long and graduated in centimeters and tenths of centimeters, was used for measuring the stalks. Measurements were made by metric scale, since the 0.1 cm. graduations are smaller and make it more precise and convenient than the English units. Readings in centimeters were converted to inches or feet when desired. The stalk length was measured from the head of the datum nail to the top edge of the highest visible leaf ligule ("dewlap" or "transverse mark"). (See Fig. 14.) Note that as soon as the ligule mark on leaf "B" appeared between leaves "A" and "C" the point of measurement was shifted from the ligule on leaf "A" to the ligule on leaf "B." As the shoots grew longer, wind and the cane's weight combined to produce curvature of the stalks. Care was taken, in measuring such stalks, to make the tape follow the curves closely and along the same side of the stalk at each observation.

When from one to two meters of stalk were formed, a datum mark was made on the hard rind below the lowest adhering leaf. (See Fig. 14.) With each additional gain of sufficient millable stalk, a new datum mark was made in the same way. Thus, for any observation of stalk length, it was possible to save time and effort by measuring the distance from the highest datum mark to the last ligule. The height of the datum above ground having been recorded, the sum of the two distances was the length of stalk.

The principal object of the growth measurements was to obtain a curve of average lengths against time, the slope of which measured the growth rate of the cane. It was desired by means of this curve to detect the critical points at which the growth rate changed. Furthermore, the observers were interested, first, in the rates of growth between two consecutive irrigations, and second, in the progress of those stalks which would survive to harvest. Hence, if a stalk began to show evidence of being a weakling, very soon to die, it was replaced by a more healthy-appearing stalk. Broken or otherwise damaged stalks were replaced as soon as the injury was discovered. Tasseling caused some disturbance, in that just prior to emergence of the tassel the leaf bundle increases tremendously in length, raising the last ligule abnormally, within only one or two days. After tasseling, the stalk ceased to grow. Tasseling stalks were replaced immediately.

Methods of Recording and Plotting Data: As soon as possible after the observers returned to the office, the data in the field notebook (Fig. 16) were transferred to a daily ledger. Information on this ledger was then plotted immediately on a large scale chart. The data plotted were:

1. Average length of 20 stalks.
2. Per cent soil moisture. (Average of four determinations.)
3. Rainfall.
4. Day-degrees (maximum temperature minus 70° F.).

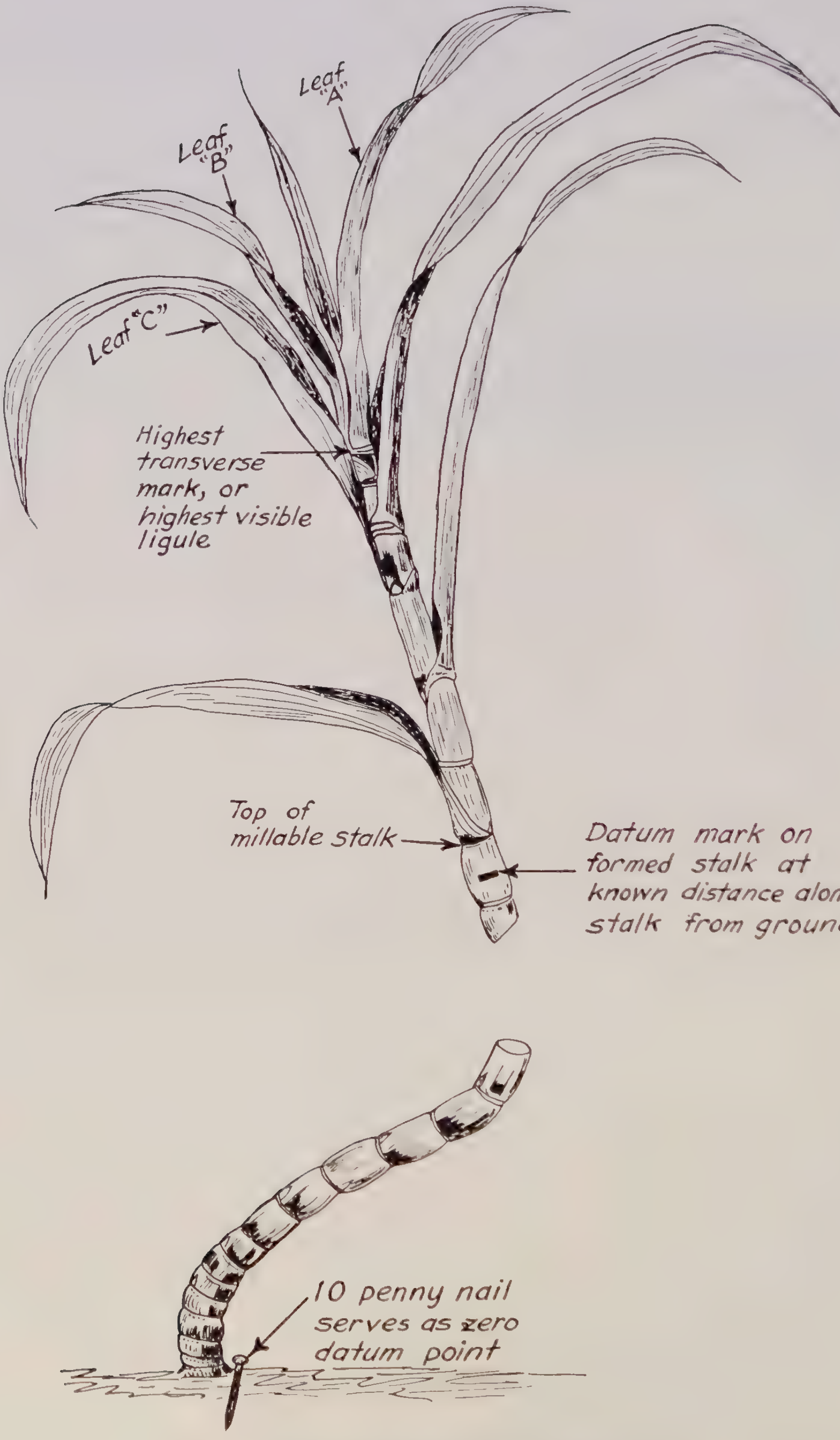


Fig. 14. Cane stalks showing points of measurement.

Fig. 15. Measuring young cane. ''O'' end of tape held on head of datum nail.

A second ledger was maintained on which were posted monthly totals of growth, rainfall, day-degrees and other information. It summarized concisely the progress of the crop.

Posting and plotting the observed data within a few hours of obtaining it were found to be of inestimable value in knowing and analyzing the conditions which prevailed from one day to the next in the vicinity of each observation station.

Results of Investigation

Plant and Water Relationships:

Earlier studies described in this report demonstrated that cane growth is independent of soil moisture content above a critical value inherently characteristic of soil type.

Relation of Cane Growth to Maximum Field Capacity and Wilting Percentage: Within a few months after commencement of observations at Waialua the charts and data began to show evidence that there existed in commercially operated fields the same relationships between soil moisture and cane growth as were established under carefully controlled conditions in the earlier studies. The present evidence is seen in a typical portion of the chart (Fig. 17), which was selected more or less at random from the large number produced during two years of study at six stations. This

5 45 a.m.

Sta. No. H-1 (Hele.2-A) Date 4/18/36

Stalk No	L	Stalk No	L	Stalk No	L
1	319.0	11	352.0		
2	214.5	12	331.9		
3	335.0	13	356.1		
4	175.5	14	210.9	Total	Datum
5	278.0	15	226.5	Height	
6	314.2	16	352.2		
7	83.5	17	217.5	= 3241.7	
8	325.5	18	304.5		
9	372.0	19	308.0		
10	329.5	20	263.0		
Total			8911.0		
Aver.			445.6		

Can No.	% Moisture	Can No.	% Moisture
51	34.9	67	35.8
52	34.1	466	33.7
Aver			34.6

Rain .02	Max T 81	Min T 60	° Day 11

Evaporation Gauge

St. -.17	Rd. -.34	Dif. +.17	Evap. In. .19

REMARKS: Clear, No Wind

Fig. 16. Facsimile page from field observation book, showing data taken in fields, and completed in office.

chart is practically self-explanatory, but there are several points to be called particularly to the reader's attention:

The moisture equivalent of the soil at each station was used to predict the maximum field capacity and the wilting percentage. These values were plotted as con-

tinuous lines in the upper part of the chart. These were the predicted limits of soil moisture available to the cane plant. Daily soil moisture contents were plotted on the same coordinates.

In the lower portion of the chart the average length of stalk was plotted, forming a curve. The slope of this curve at any point measures the rate of growth of the cane. The arrows indicate dates of irrigation.

Notice that on the dates of irrigation the soil moisture rises to about the predicted maximum field capacity. The cane plant depleted the soil moisture at about a constant rate to the predicted wilting percentage. The rate of depletion then decreased decidedly until the next irrigation, when moisture was replenished to the maximum field capacity. Evidently, when the cane roots had extracted moisture to the wilting percentage they encountered difficulty in obtaining any more moisture from the soil and consequently there was very little, if any, further depletion. Very appar-

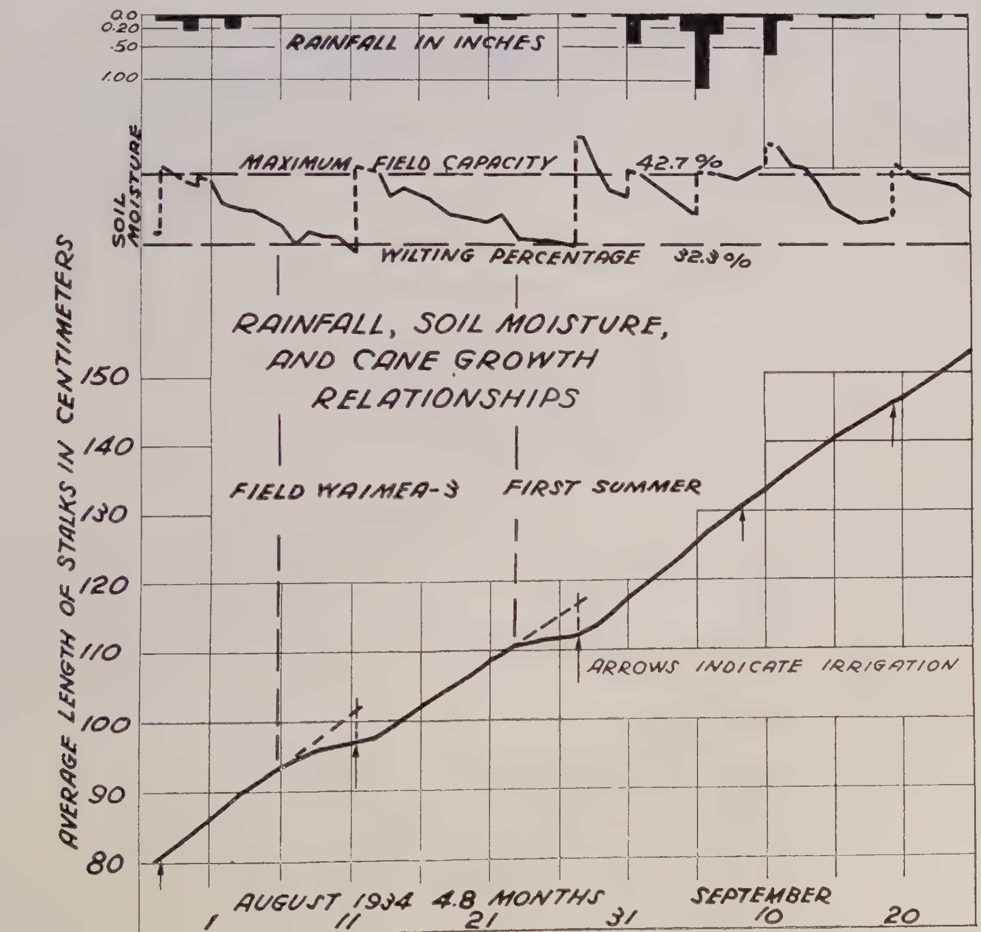


Fig. 17. First summer growth and soil moisture history shows constant rate of growth with ample soil moisture, depressed rate of growth with inadequate moisture, and effect of heavy rain in replenishing soil reservoir. Significance of depressed growth due to inadequate soil moisture is shown by indicating amount of growth which might have been made had irrigation been applied when moisture reached wilting percentage.

ently the wilting percentage constituted a lower limit to the soil moisture readily available to the cane plant.

Substantiation of Soil Moisture Philosophy as Previously Established Under Controlled Conditions: The growth curve appearing in Fig. 17 shows definite responses of the cane plant to soil moisture conditions which provide a reasonably conclusive proof of the philosophy discussed above. It can be seen that after irrigation the curve of average length was a straight line, indicating a constant rate of growth. A critical point on the growth curve was reached where the slope changed and became flatter, indicating retardation in the rate of growth. Notice the very significant fact that the date of this critical point approximately coincided with the date on which the soil moisture was depleted to the wilting percentage. Beyond this date the cane roots were unable to extract moisture readily from the soil, and the result is seen on both curves. The moisture depletion was materially reduced, or stopped altogether, and the rate of growth was depressed. When the next irrigation was applied, the moisture rose to the maximum field capacity. With soil moisture again available to the roots the plant resumed a rapid, constant rate of growth.

The philosophy of the interrelation of cane growth and soil moisture as discussed above and demonstrated many times by observed phenomena may be expressed briefly as follows:

1. As long as soil moisture is above the wilting percentage, the lower limit of availability to the plant, stalk elongation will proceed at a constant rate which is independent of the amount of moisture above the wilting percentage, but is dependent on weather conditions, age of the cane, season of the year, or a combination of factors. Soil moisture is also correspondingly depleted at about a constant rate.

2. When soil moisture is depleted to the wilting percentage, it becomes inadequately available for the plant to maintain a normal rate of growth. Growth is depressed as long as moisture is insufficient.

3. When the soil moisture is replenished above the wilting percentage, cane growth resumes a rapid constant rate dependent on conditions other than the amount of available moisture.

The transitions in growth rates on the average length curve were not always sharp or abrupt changes, depending apparently on the extent of the root system. The root system seemed also to have some influence on the degree of growth retardation accompanying periods of inadequate soil moisture.

Rainfall is seen on the chart to have increased the amount of moisture in the soil, depending on the amount of rain received. After the rain stopped, depletion of moisture proceeded at the same rate as before the rain. Light showers appear to have prevented a severe reduction in rate of growth, during some periods of inadequate soil moisture, although they were not effectual in replenishing the soil reservoir.

Verification by Cane Growth Checks of Wilting Percentages Predicted from Moisture Equivalent: Table V shows the observed percentages of moisture coincidental to critical points of change from rapid to slow cane growth, due unquestionably to insufficient soil moisture. Comparison with the predicted wilting percentages, shows that for the majority of Waialua soils the wilting percentage can be predicted from the moisture equivalent with reasonable reliability. A ratio of 1.20, rather than the general figure of 1.25 mentioned previously in this report, was used as being more indicative of Oahu residual soils.

TABLE V

COMPARISON OF OBSERVED WILTING PERCENTAGES AGAINST PREDICTED WILTING PERCENTAGES AT WAIALUA

		Field Waimea 3		Field Kawailoa 3		Field Gay 7	
Moisture Equivalent			38.8		33.3		33.5
Predicted Wilting Percentage = M.E. ÷ 1.20 =			32.8		27.8		27.9
Observed Wilting Percentages							
Year	Month	Date	% Soil Moisture	Date	% Soil Moisture	Date	% Soil Moisture
1934	May			23	29.4		
	June	14	32.9	13	27.5		
				22	29.7	22	27.8
	July	2	35.3	7	27.0	12	27.8
		20	34.3	16	28.8	21	28.5
				26	27.0		
	August	7	32.3	4	27.0	8	27.0
		23	33.2	13	27.3	29	25.2
				28	24.7		
	September			14	27.4	16	27.5
				26	29.1		
	October	1	34.5	8	28.3	5	27.8
	November			3	29.3	5	26.7
						24	29.7
	December			12	28.0	18	27.0
1935	February	14	34.1				
	April			11	29.1		
				27	27.2		
	May			13	27.5	1	25.4
				24	28.3	23	25.4
	June	13	33.4	9	27.5	7	29.2
				22	27.5	22	28.7
	July	27	32.8	5	28.6	20	26.6
				22	27.9		
	August			15	27.5	3	26.8
				17	28.9	19	28.0
	September					11	30.8
						25	28.6
	October	3	32.8			10	29.8
Average Observed Wilting Percentage			33.5±0.20		27.9±0.15		27.7±0.23
Divergence from Predicted Wilting Percentage			+1.2		+0.1		—0.2

COMPARISON OF OBSERVED WILTING PERCENTAGES AGAINST PREDICTED WILTING PERCENTAGES AT WAIALUA

		Field Mill 2		Field Helemano 2-A		Field Opaeula 13	
Moisture Equivalent			36.1		35.3		41.8
Predicted Wilting Percentage = M.E. ÷ 1.20 =			30.0		29.4		34.8
Observed Wilting Percentages							
Year	Month	Date	% Soil Moisture	Date	% Soil Moisture	Date	% Soil Moisture
1934	July	28	32.4				
	August	7	31.6			9	34.6
	September	23	32.0			12	33.4
						29	36.6
	October	10	31.1	10	29.9	17	33.5
	November	8	32.0				
	December			14	29.9		
1935	April	27	30.0				
	May			23	29.2	4	34.9
	June	12	30.3	19	28.1		
	July			20	31.5	30	35.1
	August	26	31.6	3	30.4	15	33.4
	October			8	31.2		
	December			1	31.1		
1936	June			5	27.6		
Average Observed Wilting Percentage			31.4±0.20		29.9±0.31		34.5±0.23
Divergence from Predicted Wilting Percentage			+1.4		+0.5		—0.3

Suggested Use of Soil Moisture in Determining Proper Irrigation Interval: The practical application of the fundamental relationships between cane growth and soil moisture as observed in this investigation lies in the fact that if it is desired to keep the cane growing without any cessation which might be ascribed to inadequacy of soil moisture, then it is necessary to irrigate on or slightly before the date on which the soil moisture is depleted to the wilting percentage. Referring now to Fig. 17, the proper irrigation interval would be the number of days elapsing between an irrigation and the date on which the growth rate begins to decrease, soil moisture being coincidentally at the wilting percentage.

How is the proper interval to be readily determined? First it is necessary to establish the value of the wilting percentage at the location in question. Then, any series of soil moisture observations can be extrapolated to predict the day on which the wilting percentage probably will be reached. Cane growth observations, alone, will not serve to indicate or predict the proper date on which to irrigate, but merely indicate that the wilting percentage has already been reached. A study of cane growth together with soil moisture observations serves as a check or aid in establishing the wilting percentage. Using cane growth observations solely as a guide, might result in several days' delay in irrigation on every round. A program of soil moisture sampling will produce the desired information as to proper or necessary interval; but this program should be supplemented by cane growth observations.

Winter Conditions:

This is an opportune point at which to call attention to winter conditions as related to soil moisture, cane growth, and proper or required irrigation interval. Fig. 18 shows a large portion of the first winter season in Field Waimea 3. Briefly, the following are the significant points of interest:

1. There was continuous, rather heavy rainfall throughout November 1934, and again from the middle of December 1934 to the middle of January 1935. Due to this rainfall, soil moisture was maintained at a high level for approximately 3 months. The effect of the rain continued for 15 days in February, when dry weather prevailed.

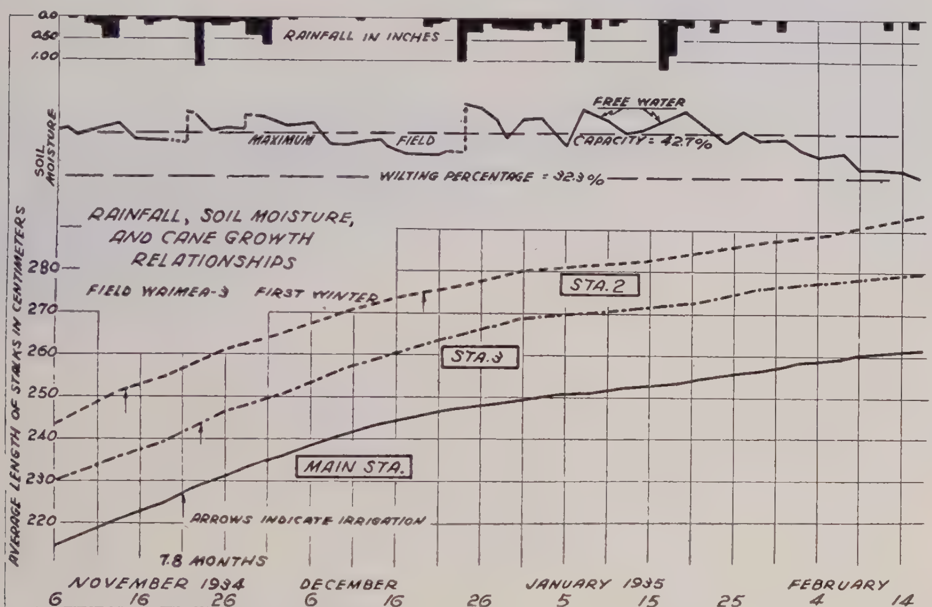


Fig. 18. No irrigation needed during continuous rainy weather which maintains high level of soil moisture. Sometimes irrigation is applied unnecessarily.

2. Most important to note is that throughout the entire period of the chart no irrigation was necessary. The irrigation on November 21 was unnecessary, as moisture in the soil at the time was ample. Even without advance knowledge as to the heavy rain which occurred two days later, the moisture curve indicated irrigation should not have been necessary for at least another 7 to 10 days, with dry weather prevailing. The moisture curve during the dry weather from January 25 to February 14 indicates that at the prevailing rate of depletion an irrigation should be applied on February 16. This is the first irrigation that was necessary after the application made on November 5.

3. This chart shows that, with an established program of soil moisture observations as a guide, it should be possible to irrigate much less frequently during the winter when rainfall maintains soil moisture more amply than is usually accredited to it.

On Fig. 18 are plotted growth curves of the substations in Field Waimea 3. The rates of growth during this period were about the same as the rate at the main station. This was found to be true, in general, in the other five fields throughout the crop. Apparently the single main stations indicated satisfactorily the progress of the crop for their respective fields.

Long-Period Curves:

Attention has been called in Fig. 17 to a number of times when soil moisture was depleted to the wilting percentage, and remained at or below that limit for several days with concurrent reductions in rate of growth. It was also mentioned that if it be desired to keep the cane growing without cessation, irrigation should be applied on the date when soil moisture reached the wilting percentage. Inability to irrigate until after the proper date, due to any of a number of causes, results in a loss of potential cane, as can be shown by the following example:

Example of Potential Cane Lost Due to Inadequate Soil Moisture: At the station in Field Waimea 3, soil moisture was about at the wilting percentage on August 6, 1935. (See Fig. 17.) The cane growth curve shows a critical point on this date, after which the growth rate was markedly depressed. When irrigation was applied on August 11, growth was resumed at about the same rate as had prevailed prior to August 6. If it had been possible to irrigate on August 6 instead of on August 11, it may be assumed with confidence that the growth would have proceeded after the sixth at the same rate as between July 28, the date of the previous irrigation, and August 6. This is indicated on the chart by a dotted extension of the July 28 to August 6 growth curve. It is seen, then, that the average length of stalk would have been 101.6 cm. on August 11 instead of the 97.1 cm. it actually was on that date. In other words, by a properly timed irrigation it would have been possible to avoid a loss of potential cane stalk equivalent to 101.6 — 97.1 = 4.5 cm. = 1.8 inches. By this graphical method of extrapolation, a record was tabulated of "possible growth," potentially obtainable by properly timed irrigations, against the "actual growth" for the entire crop at each observation station.

Indication by Curves of Total Potential Cane Lost During Crop: During the months of June, July, August, September, and part of October, when growth proceeds at high rates, the increments of lost potential growth may appear to be small individually, but collectively they can be of great economic importance. This is shown by plotting curves of accumulated possible and actual growth (Fig. 19). On this chart the "total loss of cane" is a summation of the increments of potential growth lost throughout the crop.

Seasonal and Age Effects: The long-period curves, Fig. 19, indicate several additional points. It appears that during the first winter season, December 1934 and January and February of 1935, the rate of cane growth was essentially the same in the six fields regardless of age of cane or elevation. Kawailoa 3, the plant field, is a notable exception possibly due to inherent vigor characteristic of plant cane but lacking in ratoons. Likewise, there appear to be no significant differences in second-summer (1935) growth due to age. An interesting exception to this observation was Opaeula 13 which was started in June of 1934. This field is located at 600 to 690 feet elevation. During the summer of 1935 it produced considerably greater stalk

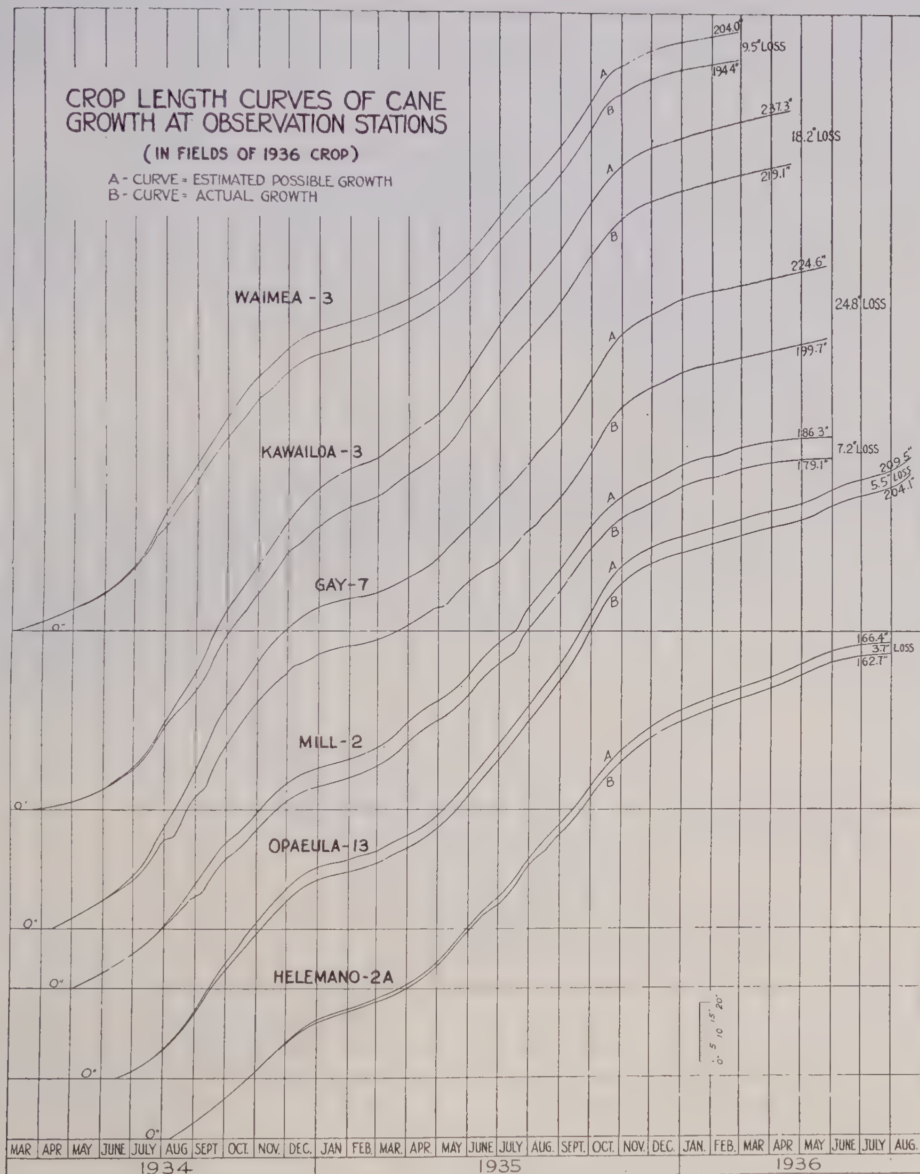


Fig. 19. Graphical crop histories showing difference between actual length of cane yielded, and amount possible with properly timed irrigations. Seasonal and age defects are seen.

elongation than the other five fields. If there is any effect of starting time to be noted from the growth records of these six fields, it would appear that for a late-started field, such as Helemano 2-A, which was started the first week in August 1934, the rate of growth could not attain as great a magnitude before the winter influence became effective. The amount of growth made by Helemano 2-A during August, September, and October of 1934 fell short of the growth made during the same months by the early-started fields. Production in a field started later than

June would appear to be dominated by two winter seasons and only one summer, whereas the earlier-started fields would be able to take advantage of two summers in addition to two winters.

Value of Rainfall as Irrigation:

Natural precipitation is a factor impossible to predict and difficult to evaluate in irrigation investigations and in commercial agriculture. Many investigators have chosen to avoid the complex problems which are presented by the variations in duration and intensity of natural rainfall. Estimates by various investigators on the effective value of rainfall range from 10 per cent to 50 per cent of the total precipitation.

Difficulty of Evaluation Because of Varying Factors: The residual moisture content of the soil before the rain occurs, the soil's capacity for water, the stage of crop development as it influences surface runoff and leaf and trash interception, and the rate of transpiration are all factors to be considered in addition to the duration and intensity of rainfall in evaluating rain as an irrigation.

Consideration of Dominant Factors: Of these factors, the residual soil moisture prior to rainfall, the soil's capacity for water, and the amount of rain received are dominant and can be measured by observation. Opinion based on observation will serve to judge the influence of duration and intensity of precipitation on these dominating measurable factors.

Light Showers Partially Effective for Growth, Ineffective for Soil Moisture: The investigations described in previous sections of this report emphasize the fact that rainfall or irrigation water added to the soil surface increases the moisture content of each increment of soil to its maximum field capacity before any water is added to lower soil increments. It follows that precipitation in an amount less than necessary to fill the entire root zone to capacity will succeed in wetting only the surface layers of soil without raising the soil moisture content of the lower root zone. Thus in a uniform soil with a residual moisture content of 5.0 per cent below its maximum field capacity, a rain of 1.00 inch might penetrate the soil to a depth of approximately 16 inches, while a rainfall of 1.50 inches would be required to wet the soil completely to a depth of 24 inches. In the same soil with a residual moisture content of 9.0 per cent below maximum field capacity, on the other hand, a 1.00-inch rain would penetrate only 9 inches, the 1.50-inch rainfall would penetrate only 14 inches, and to fill completely the 24-inch root zone, 2.75 inches of rainfall would be required.

A study of the soil moisture and rainfall records of the Waialua investigation indicates that rainfall under 0.4- to 0.5-inch is ineffective as an irrigation. At best it appears that 0.25- to 0.50-inch of rain is equivalent to but one day of interval. Although light showers from 0.10- to 0.40-inch appeared to have maintained partially normal growth during periods of inadequate soil moisture, they did not replenish the soil reservoir perceptibly.

Soil Moisture Program Preferable to Formula in Accounting for Rain: We would hesitate to offer a formula for expressing the effective value of rainfall based on the data obtained at Waialua. Such an equation would be so general as to have little use in specific cases or under localized conditions elsewhere. If all factors

were taken into account in formulating the equation, it would then become too cumbersome for easy, universal application.

We prefer to suggest that a program of soil moisture sampling will provide information as to soil moisture contents both before and after rainfall as well as the general prevailing trend of moisture depletion. With no deliberate attempt to evaluate the rainfall, a judicious interpretation of the soil moisture data will provide an index of the proper date for the next irrigation.

Effect of Temperature on Cane Growth: The maximum and minimum themometers, situated adjacent to the observation stations, provided extensive data on temperātures throughout the crop. Since Das has shown, in studies at Pepeekeo and

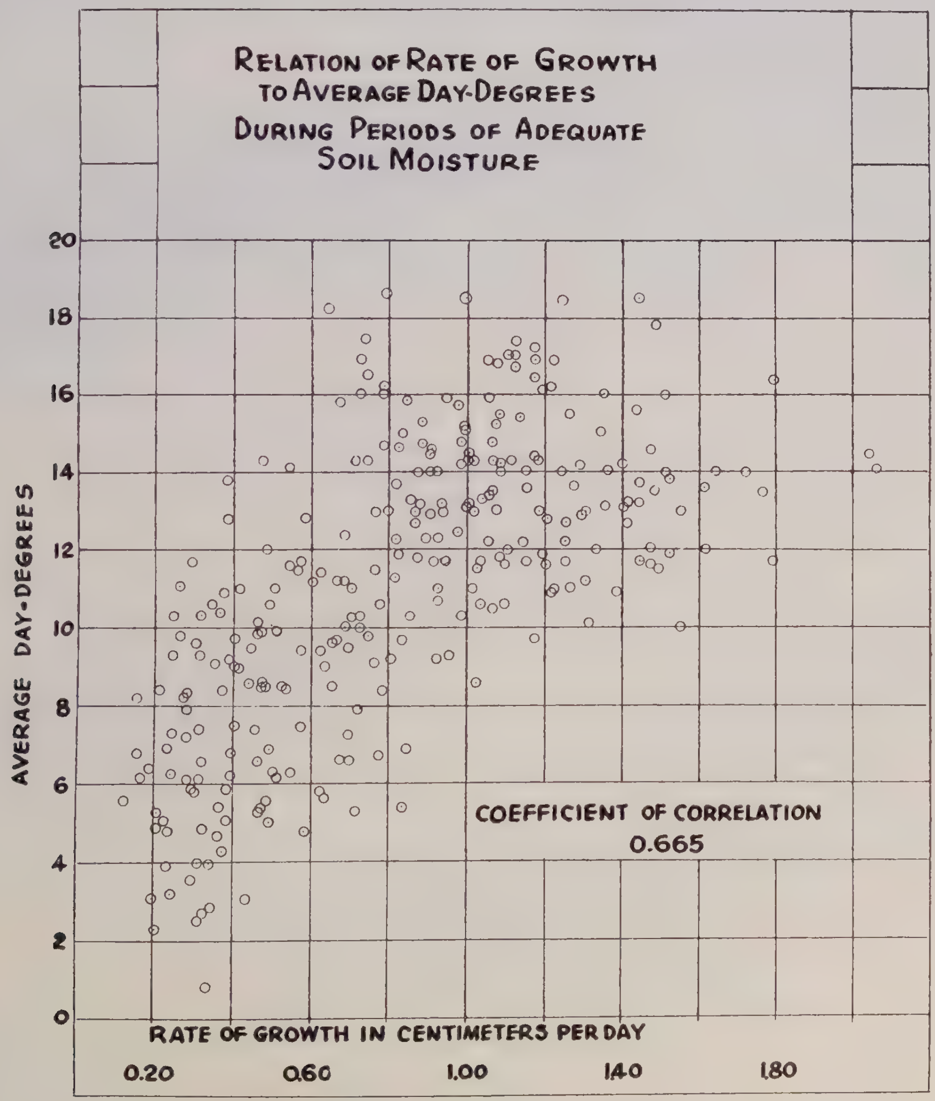


Fig. 20. A gross relationship exists between rate of growth and average day-degrees during periods of adequate soil moisture. Among individual observations there is a wide variation.

elsewhere, a high degree of correlation between growth and temperature, it was believed the Waialua data might show the following relationships:

1. A definite quantitative factor, consistent in value throughout the crop, between growth and day-degrees. This factor would be of great assistance in crop estimation.

2. A similar definite, consistent, quantitative factor between the rate of soil moisture depletion and day-degrees. This factor would be a valuable aid in determining proper irrigation intervals.

Gross Relationship for Entire Crop: All the data on growth and day-degrees at Waialua which have been analyzed are from periods of ample soil moisture, thus eliminating the complicating effect of inadequate moisture. The data show that there is a gross relationship between cane growth and day-degrees over the period of the entire crop. Table VI shows coefficients of correlation for growth against day-degrees. In general the same high degree of correlation found by Das is shown by the data. The relationship is shown graphically by plotting these observations

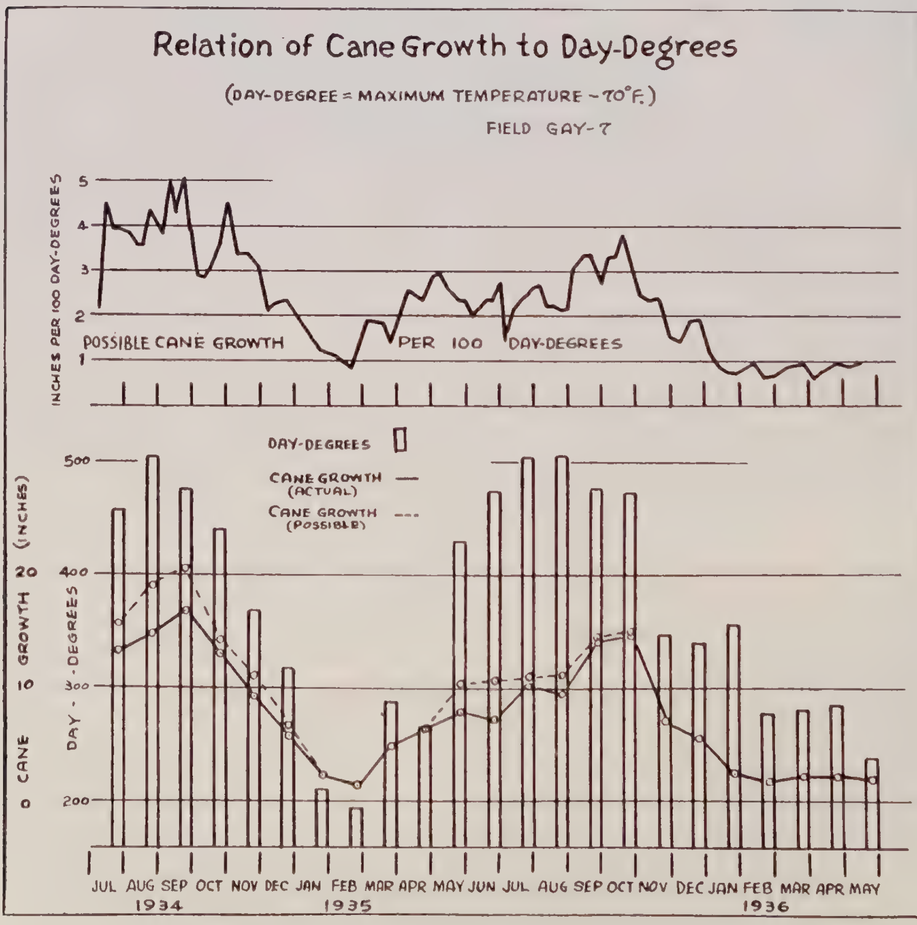


Fig. 21. Gross relationship between growth and day-degrees shown by monthly accumulations. No numerical evaluation of growth-day-degrees relationship is found to hold consistently throughout the crop.

(Fig. 20). The gross relationship is further evidenced by Fig. 21, in which the bar-graph of monthly day-degrees and the superimposed monthly growth show that throughout the crop there is greater growth during warm months than during cold months.

Difficulty in Finding Linear Relationship for Short Periods: Examination of Fig. 20 shows that, although there is a definite gross relation between growth and day-degrees, the relationship is far from precise. There is considerable variation in rate of growth made for any number of day-degrees observed. In Fig. 21 this lack of precision is shown by the curve of growth per 100 day-degrees, which fluctuates not only from season to season, but also fluctuates widely from one short period to another within a season.

TABLE VI

COEFFICIENTS OF CORRELATION

BETWEEN GROWTH PER STALK PER DAY AND DAY-DEGREES

Field	No. of Observations	Coefficient of Correlation
Waimea 3	45	0.455 ± 0.080
Kawailoa 3	50	0.887 ± 0.020
Gay 7	46	0.933 ± 0.013
Mill 2	51	0.686 ± 0.050
Helemano 2-A	45	0.754 ± 0.043
Opaeula 13	53	0.818 ± 0.031
All Stations	290	0.665 ± 0.022

The data do not offer a definitely consistent, quantitative relationship between growth and day-degrees which could be used for crop estimation.

Apparently No Consistent Relationship Between Irrigation Interval and Day-Degrees: Fig. 22 shows for a number of rounds the proper irrigation interval in terms of day-degrees accumulated from date of irrigation. Rounds were selected during which there was no rainfall to complicate the analysis. On each round, starting from date of irrigation, accumulated cane growth is plotted against accumulated day-degrees. The arrows indicate points at which irrigation water should be applied due to exhaustion of soil moisture. These points were determined in the field by the soil moisture observations, and checked by the growth observations.

These curves show that:

1. The relation of cane growth to day-degrees varies from period to period throughout the crop.

2. There is apparently no consistent number of day-degrees accumulated between irrigation and point of soil moisture exhaustion.

The variations in slopes of the curves on Fig. 22 are the fluctuations of the growth per 100 day-degrees shown on Fig. 21. The data indicate that it would be difficult to rely on day-degrees as an aid in determining proper irrigation interval at Waialua.

It can be concluded that, from the data obtained in field tests at Waialua, the day-degree is useful as a qualitative measure in comparing one crop against another. It is difficult, however, to establish a precise linear relationship between cane growth and day-degrees useful for short periods within the crop.

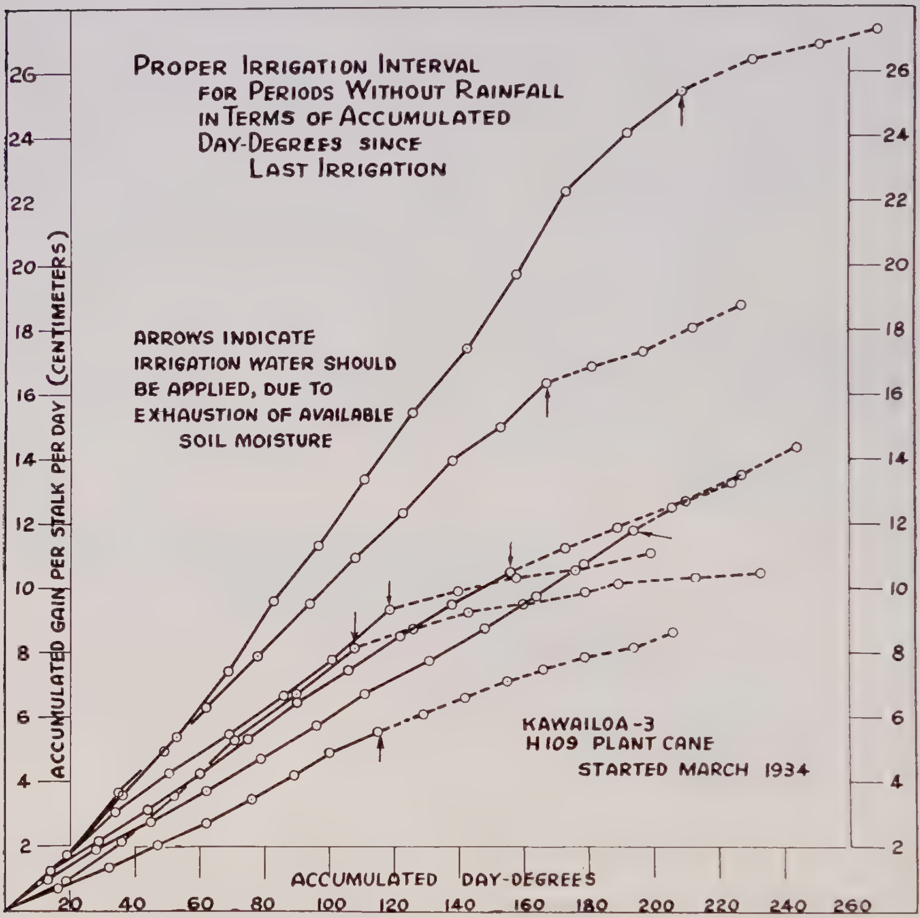


Fig. 22. No consistent numerical relationship is found to hold between proper irrigation interval and day-degrees.

Determinations at Harvest:

Measurement of Twenty Stalks at Each Observation Station: At the time of harvesting each field in which an observation station was located, the following measurements were made and recorded for each of the 20 stalks which were under observation:

1. Total length of stalk, from butt end to highest visible ligule.
2. Millable length of stalk, from butt end to lowest adhering greenleaf.
3. Length of stalk to topping point, taken as closely as possible at the same point as the actual topping being done by the regular cutters in the field.
4. The weight of the topped stalk.
5. A diameter of the stalk taken, at a purely random point on stalk.

Measurement of All Stalks in Four Random Lines: Immediately after removal and measurements of the observation stalks were completed, the remainder of the stalks in the station line were carefully removed and measured in the same way as the observation stalks. After the area surrounding the station was burned, and

before the cutting gang had reached the immediate vicinity, all stalks were removed from each of four random lines surrounding or near the station line. These stalks were measured in the same manner as the stalks from the station line.

Linear Weight of Stalk: It was desired to ascertain the linear weight (weight per foot length) of stalk, as grown under Waialua conditions. Summarizing the data taken at the harvests of the observation stations and referring to the groups of 200 to 400 stalks in the vicinity of each station, it was found that the average linear weight of stalk (in pounds per foot of length) varied from 0.48 to 0.69. It is to be remembered that the fields were harvested at various times between March 1 and September 1, and in different parts of the plantation. The linear weights at the stations were fairly well representative of the fields, but an even more extensive study of weight per foot was conducted in these same fields.

As soon as cane began to reach the mill from each field in which observation stations were located, random sticks were taken from the cars standing in the mill yard. These random sticks were obtained at the rate of one or two per car and 100 per day until the field was finished. In this way stalks were obtained from all parts of the field, the total number per field varying between 498 and 613, with a total from 6 fields of 3,446 sticks.

Each random stick from the cars was measured for length, a single purely random diameter, and weight. These data were averaged by fields, and the data summarized in Table VII.

TABLE VII

SUMMARY OF LINEAR WEIGHT OF STALK AGAINST AVERAGE RANDOM DIAMETER

Field	No. of Random Sticks	Average Diameter in cm.	Weight in Pounds per Foot
Waimea 3	594	3.29	0.584
Kawailoa 3	604	3.51	0.664
Gay 7	521	3.34	0.559
Mill 2	616	3.42	0.551
Helemano 2-A	498	3.27	0.593
Opaeula 13	613	3.30	0.476
All fields	3446	3.36	0.578

The table above by no means presents the entire information available from this study. Taking the 3,000-odd sticks individually, there was great variation in weight per foot: from 0.20 to 0.30 up to something over 1.00 pound per foot. While measuring these sticks the observers noticed what would be obvious to anyone making such measurements: that the heavier sticks were of greater girth, although lengths might be shorter than for some of the lighter sticks. With the complete sets of data at hand, and this observation in mind, the linear weights were analyzed with regard to this apparent relation to diameter. The analysis was made for each field, and also for the entire 3,446 sticks:

The linear weight in pounds per foot was computed for each individual stick. All linear weights were then classified by diameters. The classified linear weights were then plotted against corresponding random diameters. This graph indicated existence of a useful straight-line relationship. The straight lines which most nearly satisfied all pairs of diameters and classified linear weights were computed

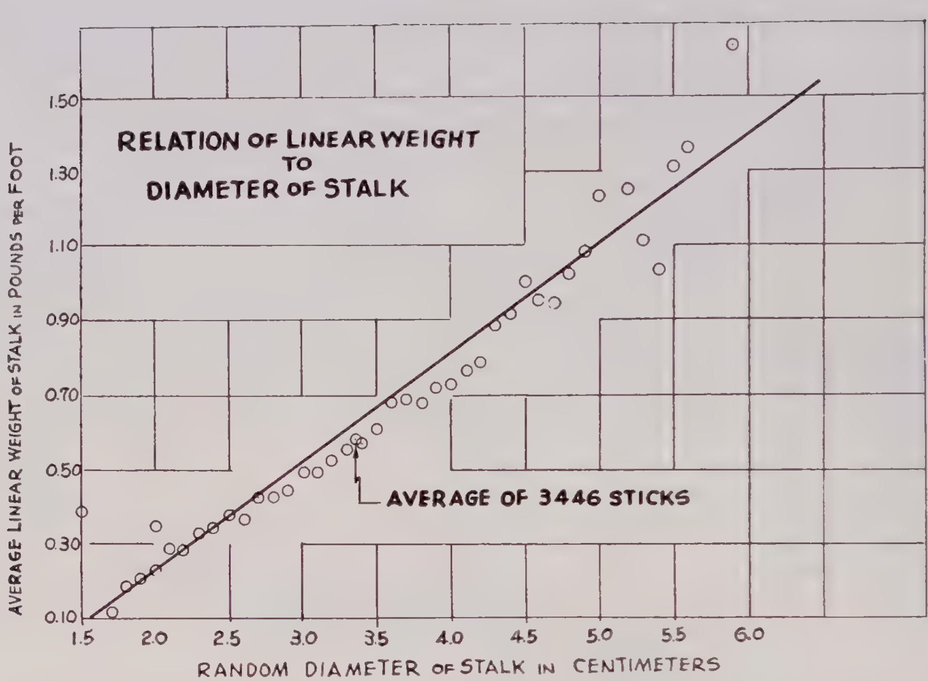


Fig. 23. Observations of random diameter of stalks in a field can be converted by this curve to give weight of stalk in pounds per foot of length.

for each field and for the entire set of data. Fig. 23 shows the graph for 3,446 sticks.

Suggested Methods of Crop Estimation: An estimate of cane yield can be made by the following formula: The yield in tons cane per acre = number of stalks per acre × average length of stalk × linear weight of stalk ÷ 2000.

Since the linear weight of stalk appears to be influenced by the girth, and since it is far simpler, prior to harvest, to obtain actual observations of random diameters than of linear weight, the observations of diameter when referred to the linear weight vs. diameter curve readily give a value, characteristic of the individual field for the linear weight factor in the yield formula. The number of stalks per acre can be obtained by stalk counts in random lines.

Another method of determining the relation between stalk length and yield of cane is to obtain the ratio of the length of representative stalks in the field to the resulting yield of cane, expressed as tons per acre of cane or sugar per unit length of stalk. The method presupposes a relatively constant relationship between length and weight of each stalk, and a relatively constant stalk population in all fields at harvest. The data must be obtained from many representative areas over a period of several crops before they can be employed safely in crop estimation. The method has been used with success on a number of Hawaiian plantations, notably the Honokaa Sugar Company and the Ewa Plantation Company.

The ratio between average length of 20 measured stalks at the observation stations and the yield of cane per acre in the six fields, 1936 crop at Waialua, is seen in Table VIII.

TABLE VIII

RELATION OF LENGTH OF OBSERVED STALKS TO FIELD YIELD

Field	Average Length of 20 stalks	Field Yield Tons cane per acre	Ratio, Tons of cane per inch of measured stalk
Waimea 3	194.43 inches	88.23	0.45
Kawailoa 3	219.07	105.35	0.48
Gay 7	199.72	89.29	0.42
Mill 2	179.05	101.40	0.56
Helemano 2-A	162.68	79.31	0.49
Opaeula 13	204.06	88.39	0.43

Effect of Inadequate Soil Moisture on Cane Tonnage: From this rather consistent relationship between length of stalk and final cane yield, a crop production chart for each field under measurement was made. Fig. 24 is an example. This chart shows the tons of cane per acre produced each week of the crop, and the number of days each week in which the soil moisture content was above the wilting

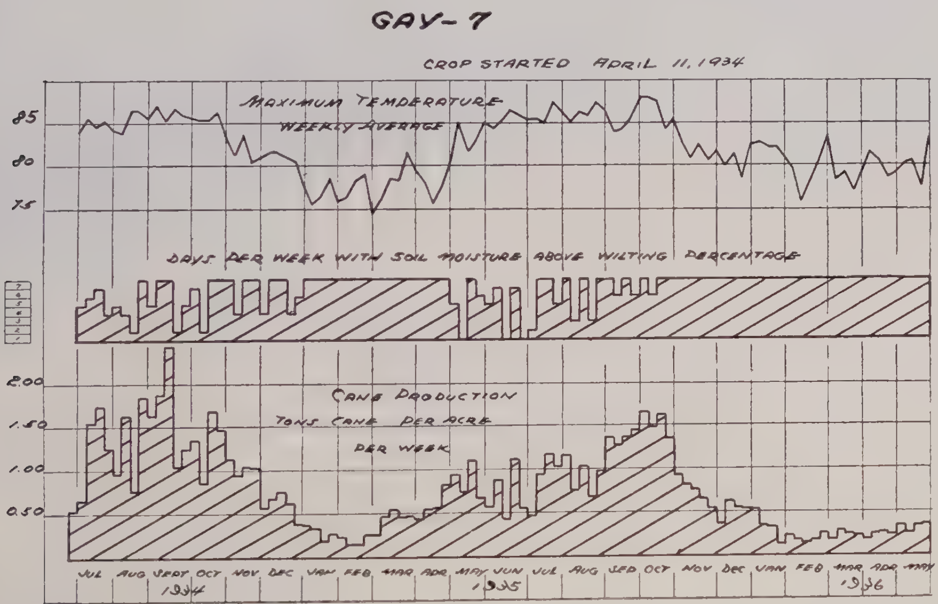


Fig. 24. Amount of cane produced is affected by number of "idle days" during which soil moisture was inadequate.

percentage. The marked effect of inadequate soil moisture in depressing the yield of cane is clearly shown. The total number of "idle days," or periods of soil moisture inadequate to promote maximum cane growth, and the potential cane tonnage lost because of inadequate soil moisture are shown in Table IX.

TABLE IX

PROBABLE LOSSES OF CANE DUE TO INADEQUATE SOIL MOISTURE

Field	Number of "Idle Days"	Probable loss because of Inadequate Soil Moisture: Inches of Stalk	Tons Cane per Acre
Waimea 3	53	9.5	4.28
Kawailoa 3	94	18.2	8.74
Gay 7	112	24.8	10.42
Mill 2	34	7.2	4.03
Helemano 2-A	36	3.7	1.81
Opaeula 13	47	5.5	2.36

This is an amplification of the information already described in Fig. 19, and indicates pointedly the economic importance of the potential cane lost. A program of soil moisture observations should be of great assistance in reducing the number of "idle days," resulting in reduction of these losses and in increased cane yields.

In Fig. 24, notice the pronounced tapering-down of cane growth. Although this would normally be expected during the "drying-off period," it is of note that the soil moisture was maintained above wilting percentage by rainfall throughout this period. There were few, if any, "idle days" due to inadequate soil moisture. Possibly the cane had consumed from the soil very nearly all of the plant nutrients before "drying-off" was commenced.

THE ADMINISTRATION OF PLANTATION IRRIGATION WATER

By H. R. Shaw

Application of Scientific Tools to Commercial Irrigation

We have discussed at some length the methods by which soil moisture and cane growth determinations may be obtained in the field, the results of preliminary studies on fundamental characteristics of growth and moisture relationships on Hawaiian plantation soils, and especially the application of these studies to commercial areas of the Waialua Agricultural Company.

It must not be thought, however, that such measurements in themselves can be a complete and satisfactory answer to the problems of water distribution and application on the plantation. Nothing can, nor should, replace careful observation and supervision in the field. The intelligent management of individual fields by division overseers and their subordinates remains the basic factor of irrigation administration.

Value of Scientific Information to Field Overseer

The plantation management owes certain considerations to its field superintendents and overseers if maximum irrigation efficiency is to be obtained. The division overseer is entitled to a proportionate share of the plantation water supply on the basis of the area he is expected to irrigate, he is entitled to the careful construction and installation of supply ditches and irrigation methods which will assure adequate distribution of water to and within the field, and he is entitled to all the information available on the water requirements and characteristics of the soils and crops with which he is working. It is in supplying and coordinating this information over the entire plantation that the scientific tools of water measurement, soil moisture analyses, and cane growth measurements may be used to obtain higher irrigation efficiency and lower production costs.

Fundamental Considerations in an Irrigation Control Plan

This paper describes the methods of irrigation administration and control now in use on the plantation of the Waialua Agricultural Company. The methods are a slow but logical development over a period of four years, and are subject to considerable further improvement and refinement. The plan of irrigation control is based on several fundamental considerations:

1. *Practicability:* The worth of each operation in irrigation control must be weighed by its value in dollars and cents to plantation field irrigation.

2. *Simplicity:* The division overseer is not a field clerk. Reports from the field must be brief and simple, and should be in a form readily understood and submitted by the irrigator or ditchman.

3. *Applicability:* Irrigation reports are not contributions to ancient history. Data must be capable of immediate application to field operations, of anticipating difficulties, and of correcting errors before they have accumulated.

4. *Flexibility:* Irrigation deals with variable factors of weather, cropping plans, labor and water supply. Irrigation control must be designed to accommodate itself without lost motion to changes in conditions.

Irrigation control and administration at Waialua may be divided into three separate but correlated phases: (a) water measurement, (b) use of water, labor, and cropping data, and (c) use of investigational data.

Water Measurement at Waialua

Types of Measurement:

The rectangular weir, the rated section, and the submerged orifice have long been considered by irrigation engineers as the standards of water measurement in the field. There are, however, many disadvantages to these types of measurement which limit their utility in actual practice. The use of the rectangular weir entails a considerable loss in head, the elimination of velocity of approach, and the frequent removal of silt deposits in the approach basin. The rated section, in which water discharge is determined by measuring the rate of flow over a known cross-section is designed primarily for the measurement of large streams and rivers. The submerged orifice is affected by velocity and direction of approach, by silting and blocking of the orifice, and has a limited flow accommodation. The Venturi meter, in which discharge and rate of flow are based on the pressure differential on either side of a constricted section of closed pipe, is used chiefly for the measurement of pump discharge. When properly installed and maintained, this device is probably the most accurate means of water measurement available; however, its relatively high cost limits its utility to large pumps and pipe lines where in necessity, precision of water measurement outweighs its original cost.

The Parshall measuring flume, formerly called the Improved Venturi flume, was developed by Ralph L. Parshall, Senior Irrigation Engineer of the U. S. Department of Agriculture, in the Hydraulic Laboratory at Fort Collins, Colorado. The first installation locally was made on the plantation of the Hawaiian Commercial and Sugar Company in 1927, and its use and popularity have since spread throughout the Hawaiian Islands. The Parshall flume is arbitrary in design, and specifications

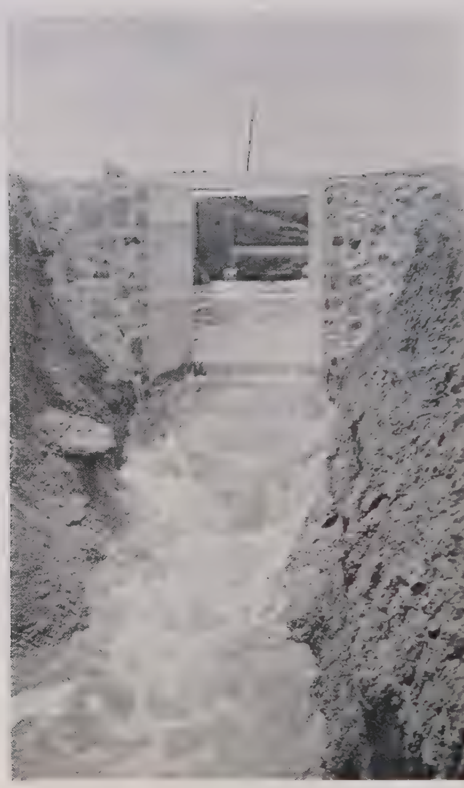


Fig. 25. Parshall flume installation with additional wall height, for measurement of freshet peaks in mountain water ditches.

must be followed implicitly; but from exhaustive tests both on the Mainland and in Hawaii this device appears to be the most practical and accurate means of measuring water in open channels. The Parshall flume is as accurate as the weir, requires but little loss in head, is little affected by velocity or direction of approach, is self-cleaning, and accommodates large fluctuations of flow. The Parshall flume is the standard type of water measurement in use at Waialua; methods of installation and use are described later in this report.

All of the types of measurement mentioned above require a graphical recording device in order to secure proper records of water discharge. Such a record, in addition to registering the head of water passing each control point, gives a complete history of flow, registers flow peaks and night water, and is valuable in planning water distribution and in settling disputes. Several types of graphic registers are manufactured, and are available through local agents. The methods of reading and the use of recording charts at Waialua are described later in this report.

Installation of the Parshall Measuring Flume:

Technical details of the development, specifications, and installation of the Parshall measuring flume are contained in Bulletin 336 of the Colorado Agricultural College Experiment Station by Ralph L. Parshall.

Early installations of the Parshall flume in Hawaii were made of redwood. As the usefulness of the device became apparent, a more permanent structure was desired. Several individual plantations as well as the Experiment Station, H.S.P.A., developed steel forms from which concrete structures could be cast in place. Usually the floor is cast at the proper elevation, the steel forms set at the desired throat width, and the sidewalls to the required height cast in place. As the angles of the sidewalls do not change with increasing throat widths, a set of cross-members to give

Fig. 26. Parshall flume with concrete floor and redwood sides, for mountain locations.

throat widths of various sizes permits the construction of measuring devices which will accommodate any range of flow found under ordinary plantation conditions.

A modification which increases the utility of the Parshall flume in measuring great fluctuations of flow, such as are found in mountain ditches with a normal low flow but with occasional freshet peaks, is the use of a relatively narrow throat with sidewalls higher than the standard 2.5 feet. Thus the head of water under normal low flows is great enough for accurate measurement, while freshet flows can be accommodated without flooding the structure and can be measured with sufficient precision. In a personal letter to the writer, Mr. Parshall comments on this modification of the Parshall flume as follows: "I see no theoretical or practical reason why you cannot use the flume for heads of more than 2.5 feet. My suggestion would be to increase the length of the converging section. This will smooth out the stream

Fig. 27. Parshall flume installation—casting sidewalls 4.5 feet high in place.

lines and give a very good hydraulic condition. It is important, however, to maintain the 'H_a' gage point at the standard distance back from the crest."

The use of a concrete floor with redwood sides for the construction of the Parshall flume in localities accessible only by pack mules or by hand carrying was first employed by the Pioneer Mill Company. This method obviates transportation of the bulky steel side forms, and permits accurate water measurement under conditions which could be met otherwise only by the use of the rated section and current meter. At Waialua, where two such structures have been installed, the sidewalls and timbers are cut to size in the plantation shops, and are packed to the site by mules or by hand from the end of the truck road. The construction of the concrete floor and the erection of the sidewalls can be made rapidly and accurately by a few men.

The construction of concrete Parshall flumes cast in place has several disadvantages. The steel forms are heavy, cumbersome, and often get out of alignment after a few years' use. The short time usually available for construction frequently prevents the concrete from curing properly before water is turned into the ditch. From three to four days is generally required for casting a Parshall flume.

To avoid these disadvantages, Waialua Agricultural Company has developed precast concrete slabs, poured to precise specifications, for field installations of the Parshall flume with two-foot throat. Thirteen slabs, having a total weight of 2,511 pounds, are fitted by dovetail joints to form each flume unit. The cost per unit at the plant is $7.03, with six man-days required for erection in the field. A precast Parshall flume may be erected and ready for use in two days.

Each measuring device installed at Waialua is equipped with a 24″ x 24″ stilling well, a meter house with hook gage, and a staff gage graduated in units of flow rather than head for the use of ditchmen and overseers. A graphic water-level recorder is not necessarily installed at each flume but may be moved from one station to another as the need for continuously recorded flow and discharge arises. The meter house is of simple, rainproof construction with ample room for maintenance of the meter. The hook gage is a ¾″ x ¾″ wooden rod with an inverted brass hook at the

lower end. The difference in elevation between the floor of the Parshall flume and a convenient point on the platform of the meter house is obtaind by an engineer's level. With the extension of the point of the hook to the rod as zero, the difference in elevation is marked in hundredths of a foot on the rod. The hook-gage rod is placed vertically through a square hole in the house platform with the brass hook in the water of the stilling well. The rod is adjusted so that the point of the hook just pierces the surface of the water, and the head of water is read directly from the

Fig. 28. Setting crest and floor, precast Parshall flume.

rod at the platform datum. The staff gage is graduated in units of million gallons per 24 hours and, in many cases, in units of acre-inches per hour so that no discharge tables are required by the ditchman or overseer to determine the flow of water through any station on his division. Two types of staff gage are in use at Waialua. One developed by Engineer C. A. Brown of Pioneer Mill Company employs a rigid wire rod attached to a small float in the stilling well and leading to the staff gage on the meter house platform. As the water level rises or falls, the indicator on the upper end of the rod points to the rate of flow. The other type is a stencil in units of million gallons per 24 hours which is painted at the proper point on the wall of the approach section in the flume, and is renewed when necessary.

Classes of Water-Measuring Stations:

Three classes of water-measuring stations are in use at Waialua. The Distribution System has 28 stations, chiefly two-foot and four-foot Parshall flumes, situated at strategic locations to measure all gravity water received on the plantation and to measure water passing on each supply canal from one division to another. Each station is equipped with a weekly graphic recorder and flow staff gage, and is checked

Fig. 29. Erecting sidewalls, precast Parshall flume.

many times a day by ditchmen and overseers to insure proper delivery of water. The Pump Discharge stations, generally two-foot Parshall flumes, are installed at the outlets of pumps not equipped with Venturi meters. They may or may not be equipped with recorders, and are used chiefly to check rates of flow and to determine whether or not a pump is delivering its rated capacity. Field measurement stations, chiefly precast two-foot Parshall flumes, are installed at the head of representative fields of different soil types and under different methods of irrigation to determine net water requirements of plantation areas and to check the efficiency of field irrigation. Most of these stations are equipped with recorders, although the meters may be moved from site to site as the need arises. Other stations are installed to fill specific tasks such as checking the distribution of water through important reservoirs and straight ditches, measuring seepage losses, and determining the size and constancy of potential sources of water supply.

Reading Meter Charts:

The chart from most water-level recorders is a continuous graph of height of water passing through a measuring station against units of time. In no type of measuring device is the discharge of water directly proportional to the head. Therefore, it is never correct to compute water discharge by obtaining the average head over a given period of time and noting the discharge equivalent to the average, nor is it correct to trace the graphic record of water heights with a planimeter and

Fig. 30. Parshall flume with recording meter, staff gage and hook gage for use in irrigation control.

compute discharge from the entire area under the curve. The true discharge of water for any period of time must be determined from the sum of discharges equivalent to each change in water height.

A rather simple, accurate, and rapid means of determining and recording water discharge is used at Waialua. The recorders are equipped with pencils so that the records may be erased and used again. It is desirable, however, to have a permanent record of flow in each ditch not only for checking results but in order to re-create the flow curve if necessary. In reading the charts we use a "discharge overlay," which is a two-inch strip of meter-chart paper with the equivalent discharge of water for the measuring device and gage-height ratio in use indicated for each increment of height. The "flow sheet" is a mimeographed form with spaces for identification of the measuring station and for entries of the rate and duration of each stage of flow throughout the week. The discharge overlay is placed on the meter chart with zero lines coinciding and is moved along the chart in that position until the pencil record of water heights intersects the equivalent discharge on the overlay. Discharge is expressed in "acre-inches per hour," which is essentially equal to the unit, "cubic feet per second," in which most discharge tables for the weir and Parshall

flumes are written. The discharge equivalent to the intersected gage-height record of the meter chart is entered in the first column of the flow sheet, and the number of hours through which this rate of flow continued is entered in the second column. In like manner the discharge overlay is moved along the meter chart, with rate and duration of flow entered on the flow sheet for each change in the height of water indicated by the pencil line. The duration of flow is usually taken in units of even hours although interpolated decimals of an hour may be used if significant changes in water height occur within the hour. The "water day" is considered as the 24 hours from 5:00 p. m. to 5:00 p. m., as delivery for each day's irrigation usually takes place within that time. When the week's record has been read and entered on the flow sheet, the rate of flow in acre-inches per hour is multiplied by the duration of

KEMOO DIVISION

W.A.CO., LTD.

MONTHLY SCHEDULE OF IRRIGATION INTERVALS

Based on 31 calendar days and 27 working days.

MONTH OF OCTOBER 1936

Crop	Field No.	Area	Age in Months	PROPOSED INTERVAL (DAYS)			Acres per Day	Acre-Mos. Sched.
				FIELDS UNDER PUMP WATER				
1938	Valley 1B	20.31	2.1	12			1.88	50.78
1937	" 1A	88.80	14.2	18			5.49	148.30
1938	" 2	26.01	4.6	12			2.41	65.03
Pali 1937	" 2AB	20.51	13.6	12			1.90	51.28
Flat 1937	" 2AB	60.13	13.6	18			3.72	100.42
1938	Old Mill	34.58	2.0	12			3.20	86.45
1937	Kemoo 1	30.47	14.5	15			2.26	60.94
1937	Kemoo 1B	107.74	15.2	15			7.98	215.48
1937	Kemoo 3	30.31	14.3	15			2.25	60.62
				FIELDS UNDER MOUNTAIN WATER				
1937	Kemoo 1A	33.52	17.3	15			2.48	67.04
1938	" 2A	50.16	4.0	10			5.57	150.48
1937	" 2B	60.21	16.5	~~15~~	12		5.58	150.53
1937	" 3	27.81	14.3	15			2.06	55.62
1938	" 4	88.94	4.5	12			8.24	222.35
1938	" 5	30.10	4.2	12			2.79	75.25
1938	" 6	76.05	4.5	12			7.04	190.13
1938	" 7	52.67	5.0	12			4.88	131.68
1937	" 8	37.78	13.3	15			2.80	75.56
1937	" 9	71.34	15.3	25	} Ripening	as of 10/15	~~3.17~~	~~85.67~~
1937	" 10	15.97	15.2	25	}		~~0.71~~	~~19.16~~

Total Acres under Irrigation 963.41 − 87.31 (10-15-36)

Total Acres Ripening 87.31 (10-15-36)

Total Acre-Months Scheduled 2062.71 − 104.77 (10-15-36)

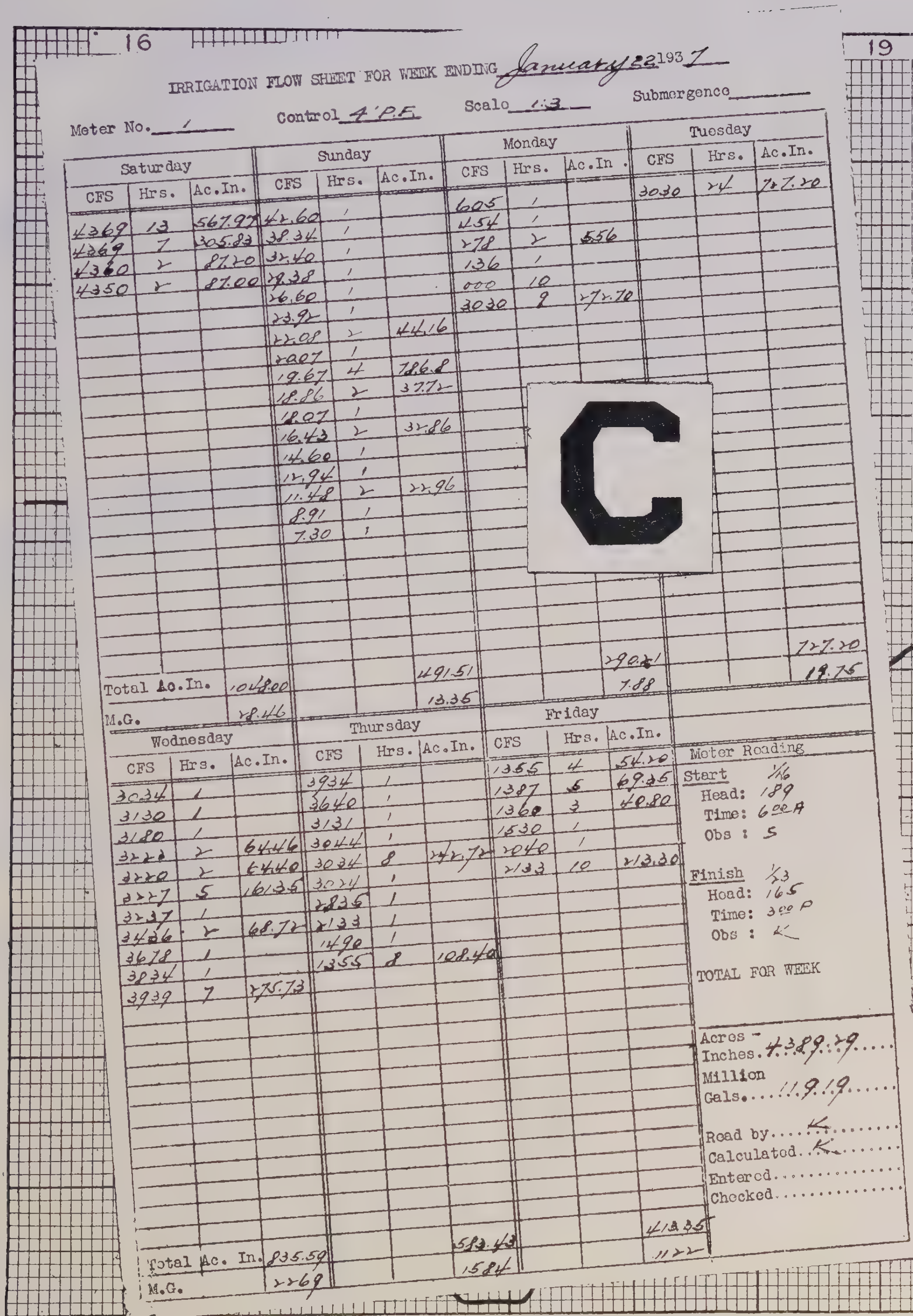
APPROVED

W. C. Irvin
Division Overseer

H. R. Shaw
Irrigation Overseer

R. D. Pritchard
Head Overseer

Fig. 32. From area to be irrigated and daily acreage to be covered, labor and water required are readily obtained. This schedule is extremely flexible.



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IRRIGATION FLOW SHEET FOR WEEK ENDING January 22 1937

Meter No. 1 Control 4'P.F. Scale 1:3 Submergence

Saturday CFS	Hrs.	Ac.In.	Sunday CFS	Hrs.	Ac.In.	Monday CFS	Hrs.	Ac.In.	Tuesday CFS	Hrs.	Ac.In.
									3030	24	727.20
4369	13	567.97	42.60	1		605	1				
4369	7	305.83	38.34	1		454	1				
4360	2	87.20	32.40	1		278	2	5.56			
4350	2	87.00	29.38	1		136	1				
			26.60	1		000	10				
			23.92	1		3030	9	272.70			
			22.08	2	44.16						
			20.07	1							
			19.67	4	78.68						
			18.86	2	37.72						
			18.07	1							
			16.43	2	32.86						
			14.60	1							
			12.94	1							
			11.48	2	22.96						
			8.91	1							
			7.30	1							
Total Ac.In.		1048.00			491.51			290.21			727.20
M.G.		28.46			13.35			7.88			19.75

Wednesday CFS	Hrs.	Ac.In.	Thursday CFS	Hrs.	Ac.In.	Friday CFS	Hrs.	Ac.In.
			3934	1		1355	4	54.20
3034	1		3640	1		1387	5	69.35
3130	1		3131	1		1360	3	40.80
3180	1		3044	1		1530	1	
3223	2	64.46	3034	8	242.72	2040	1	
3220	2	64.40	3024	1		2133	10	213.30
3227	5	161.35	2836	1				
3237	1		2133	1				
3436	2	68.72	1490	1				
3678	1		1355	8	108.40			
3834	1							
3939	7	275.73						
Total Ac. In.		835.59			583.43			413.35
M.G.		22.69			15.84			11.22

Meter Reading

Start 1/16
Head: 189
Time: 6⁰⁰A
Obs : 5

Finish 1/23
Head: 165
Time: 3⁰⁰P
Obs : K

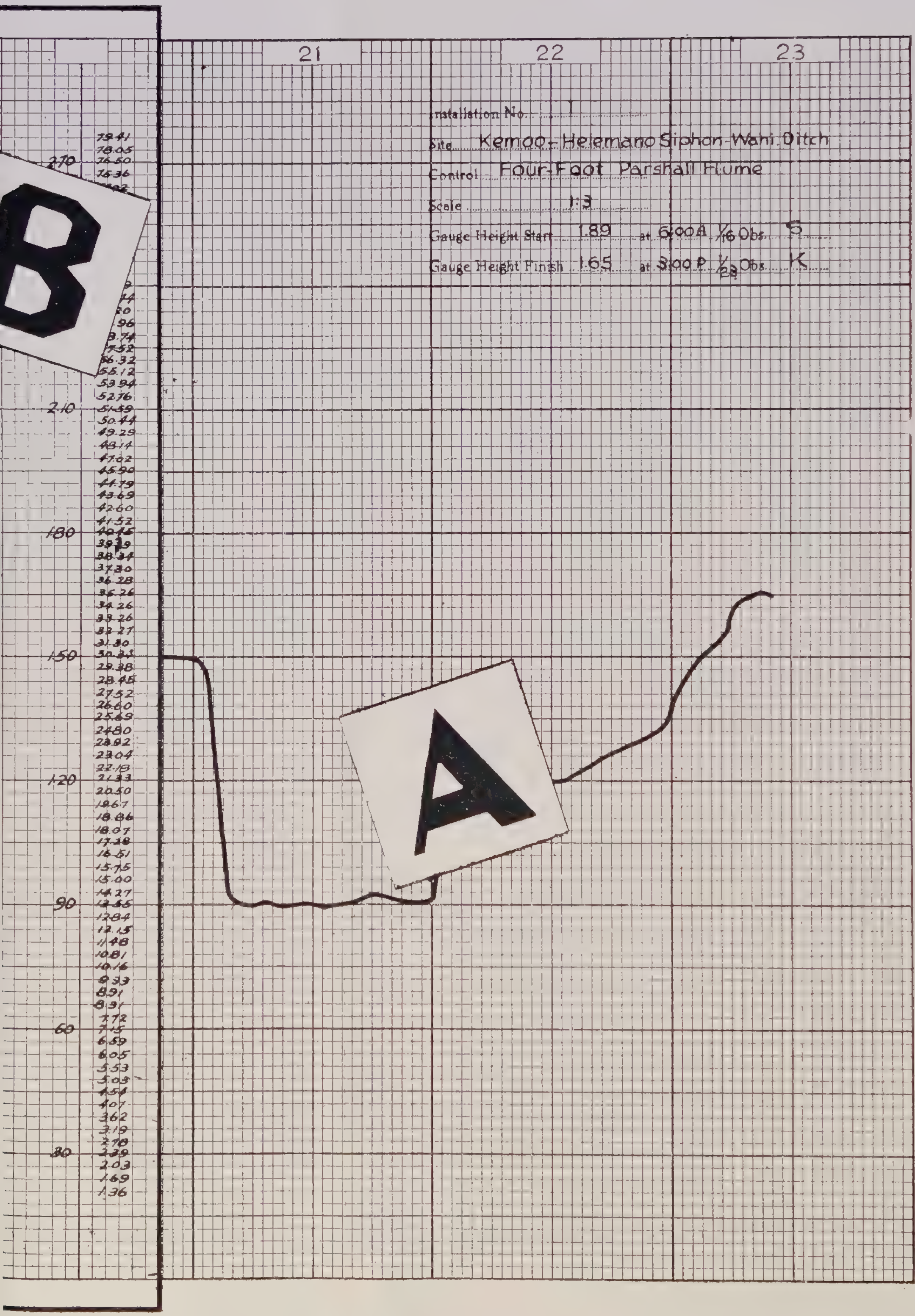
TOTAL FOR WEEK

Acres - Inches. 4389.29
Million Gals. 119.19

Read by K
Calculated K
Entered
Checked

C

Fig. 31. Flow of water is easily determined by ''overla



neter chart (A), and permanently recorded on flow sheet (C).

flow in hours and the total acre-inches delivered for each day entered at the foot of the column. Acre-inches may be converted to million gallons by multiplying by the factor 0.027.

With such a system a clerk can compute rapidly and accurately the discharge of a large number of measuring stations. The results are summarized in a "water balance" in which the daily discharge of water received and delivered on every main supply canal is posted for each plantation division. Information for the weekly reports on relation of water consumption to area irrigated and labor used, as described later in this report, is drawn largely from the Water Balance Summary.

Use of Water, Labor, and Cropping Data

Monthly Irrigation Schedule:

The chief basis of water distribution at Waialua is the "monthly irrigation schedule" (Fig. 32). The schedule lists the number, area, crop year, and age at the first of the month for each field of every division. The interval between irrigation desired for each field, or portion of the field, for the coming month is determined by the soil type, season, age of cane, and the water supply available for each area. Current investigational data on the rate of soil moisture depletion and rate of cane growth are used fully in assigning the desired interval. After the irrigation schedule is made out by the irrigation overseer, it is discussed with the division overseers, the head overseer, and the manager. Modifications or changes are noted. The total area to be irrigated during the month and the area to be irrigated daily in each field to maintain the desired interval are then calculated. The area to be irrigated daily is the key figure in planning water distribution and in checking irrigation progress. Each division overseer and water luna is informed of the area to be covered daily in each field, and of the water he will receive and deliver in each supply area to meet the desired irrigation interval. He distributes water and labor to the fields within the supply area so as to cover the daily area requirement. The irrigation schedule is very flexible, and may be changed several times during the month. As water supply increases or diminishes, as fields are added or taken out of the area to be irrigated, or as observation and investigational data indicate the desirability of increasing or decreasing the interval between irrigations, the area to be irrigated daily in each supply area is changed accordingly.

Water Distribution Tables:

A basic table of water to be received and delivered on each supply canal is prepared from the monthly schedule, and division overseers are held responsible for the proper distribution of water to the next division. The water distribution is checked frequently through the use of the measuring stations.

Field Reports:

Field reports on daily irrigation accomplished are in the simplest form possible, and are made out and submitted by the field irrigator or water luna. The ditch number and area under each level ditch, ranging from two to five acres in size, are listed in the irrigation office. The corresponding ditch number is indicated on a

stake at the entrance to each level ditch. The field ditchman reports the numbers of the ditches his men have completed, and the number of men irrigating in the field. A circle is placed around the number of ditches partially irrigated but not completed, and the ditch number reported again the following day when irrigation is completed. The reports are received early the following morning by a clerk in the irrigation office, who summarizes the daily irrigation in a time book, showing the ditch numbers completed and the men irrigating daily in each field on the plantation. The area irrigated and the labor required is totalled weekly, or at more frequent intervals if desirable.

The status of irrigation is shown in an "interval report," issued daily during the irrigation season. Our interest centers in assuring that each ditch, or similar small area within the field, is irrigated at the scheduled interval and that the information is available promptly so that errors can be corrected immediately. The interval report, issued to the head overseer, the irrigation overseer, and the division overseer concerned, shows the ditches within each field of every division which on the previous day were irrigated more than one day ahead or more than one day behind schedule. The report on each day's irrigation is available by noon of the day following the irrigation. The interval report has proved highly useful in adjusting water distribution within the division, releasing labor from irrigation for other operations, and in assuring prompt and effective action in correcting errors. The human tendency to make the field reports what the bosses would like rather than what was actually accomplished has proved discouraging to the ditchmen making the basic field report, as they found themselves in such a maze of complications that "doctored" reports soon disappeared. Of their own volition, most of the division overseers and water lunas have adopted the practice of entering in their time books the number of the ditches irrigated daily for each field in order to anticipate and prevent any of their areas appearing in the interval report.

TYPICAL REPORT USED AT WAIALUA TO CHECK IRRIGATION PERFORMANCE

Division: Kemoo Date: October 10, 1936

DAILY IRRIGATION INTERVAL REPORT

Fields Behind Schedule				Fields Ahead of Schedule			
Field	Interval Scheduled	Days	Ditches	Field	Interval Scheduled	Days	Ditches
Kemoo 2A ...	10	2	6, 7	Kemoo 2B ...	12	3	1, 2
Kemoo 5	12	4	3	Kemoo 8	15	2	10
Kemoo 7	12	1	2, 6				

Weekly Irrigation Reports:

A "weekly irrigation report" (Fig. 33) summarizes the progress of irrigation throughout the year. From the water balance are drawn data on the total amount of water received and delivered, and from the summarized field reports are shown the area irrigated and labor required on each division of the plantation. The resulting data on application of water and on performance of labor provide a guide to relative irrigation efficiency, give an experience basis on area irrigated per million gallons of water for use in water distribution, and are essential in planning cropping schedules, water requirements, and future developments.

WEEKLY IRRIGATION REPORT
WAIALUA AGRICULTURAL COMPANY, LIMITED
WATER AND LABOR DISTRIBUTION FOR WEEK ENDING 5:00 P.M., Friday October 2, 1936

	Kaw'pai	Mok.	Ranch	Kamoo	Hele.	Opae.	Kawailoa	Waimea	Plantation
Million Gals. of Water:									
Received	32.40	86.93	231.41	282.54	381.11	339.06	256.74	84.55	995.02
Delivered	1.00	5.96	73.76	194.45	197.09	172.50	91.28	3.00	39.32
Consumed	31.40	80.97	157.65	88.09	184.02	166.56	165.46	81.55	955.70
Average Applications:									
Acre-Inches Per Acre	4.76	5.80	7.25	5.92	6.64	7.80	8.56	6.37	6.91
Acres Per Mil. Gals.	7.73	6.35	5.08	6.22	5.55	4.72	4.30	5.78	5.33
Average Per Man:									
Acres Per Day	3.92	3.19	3.10	2.98	3.24	2.35	3.49	2.78	3.02
Million Gallons	0.507	0.503	0.611	0.479	0.584	0.499	0.811	0.480	0.566
Area Irrigated in % Total Under Irrigation	59.94	59.60	59.69	57.04	57.01	52.41	56.75	52.43	56.53
Average Interval (Days)	11.7	11.8	11.7	12.3	12.3	13.4	12.3	13.4	12.4
Average Crop Age	7.9	7.7	9.5	10.6	8.9	7.0	8.9	6.9	8.6
Acres Under Irrigation	404.95	863.10	1341.65	960.51	1790.29	1499.67	1254.14	899.75	9014.06
Acres Ripening or Fallow	88.70	----	67.74	----	87.49	164.96	----	----	408.89
% Total Under Irrigation	82.03	100.00	95.19	100.00	95.34	90.09	100.00	100.00	95.66
Acres Irrigated This Week	242.74	514.36	800.82	547.86	1020.66	786.00	711.66	471.72	5095.82
Number of Men	62	161	258	184	315	334	204	170	1688
Acres Irrigated This Month	71.86	180.50	256.18	178.60	352.60	276.44	210.54	197.42	1724.14
Total Acres Scheduled This Month	892.40	2052.28	3113.98	2218.54	4008.00	3487.36	2883.32	2037.80	20693.68
Per Cent Completed	8.05	8.80	8.23	8.05	8.80	7.93	7.30	9.69	8.33

H. R. Shaw
Irrigation Overseer

Fig. 33. This report assists the division overseers in balancing labor and required water so as to attain higher irrigation efficiency.

The four reports described above form the basis for irrigation administration and control on the Waialua Plantation. The data provide material for other valuable reports on the efficiency of various irrigation methods, comparisons of irrigation performance with that of past years, and on the relation between irrigation performance and crop yields.

Use of Investigational Data

The methods of soil moisture and cane growth analyses described in previous portions of these reports are of value to commercial irrigation only so far as plantation executives, division overseers, and water lunas use the information intelligently. Research and investigational data are considered merely as tools which can be used to obtain better and cheaper production. Such success as we have gained from irrigation investigations at Waialua has resulted from high standards of accuracy, from a rapid and well-organized program of obtaining and analyzing data, and from prompt reports expressed in terms easily understood and applied by field overseers to commercial irrigation.

Use of the Moisture Equivalent Survey:

The classification of all plantation soils on the basis of their water-holding characteristics as measured by the moisture equivalent has proved to be an excellent investment. Considerable pains were taken to make the survey accurate, especially since this was the first time the moisture equivalent procedure has ever been used

for field surveys on so great an area. Some of the practical applications of the moisture equivalent data to field irrigation have been:

1. As a standard of water requirements for plantation fields, the moisture equivalent provides a rational basis for estimating the amount of water required for various soil types. At the present stage of development in irrigation methods, the relative water consumption on different areas appears to be dominated more by the slope of the land, age of cane, and distribution of moisture within the area than it is by differences in the soil's ability to hold water. The net water requirement estimated from the moisture equivalent values, however, provides an index of irrigation efficiency between various cane areas.

UTILIZATION OF GROSS WATER APPLIED, WAIALUA AGRICULTURAL CO., LTD.

	Application in Acre-Inches per Acre per Irrigation				
Division	Net Requirement based on Moisture Equivalent of Soils*	Actual Gross Application, 1934	Per Cent Gross Water Utilized	Actual Gross Application, 1936	Per Cent Gross Water Utilized
1..........	3.09	5.62	55.0	6.03	51.2
2..........	3.17	7.22	43.9	5.63	56.3
3..........	3.31	8.69	38.1	7.94	41.7
4..........	3.17	8.73	36.3	5.91	53.6
5..........	3.05	9.04	33.7	6.65	45.9
6..........	3.11	8.06	38.6	7.49	41.5
7..........	3.02	8.49	35.6	8.22	36.7
8..........	3.15	6.28	50.2	5.62	56.0
Plantation.....	3.13	8.06	38.8	6.90	45.4

* Basis of estimate: Requirement (acre-inches per acre) $= \left(\text{M.E.} \times 1.1 - \frac{\text{M.E.}}{1.2} \right) \times$ Volume Weight $\times$ Desired penetration (inches).

2. As a basis for identifying "dry spots" or areas of low moisture-holding ability, the moisture equivalent survey plotted on field maps points out areas of poor soil which may require differential irrigation treatment, either by scheduling faster intervals between rounds for certain ditches or by varying the amounts of water to certain areas.

3. As a basis for eliminating marginal lands, the moisture equivalent survey is used as one of the bases of judgment in abandoning production areas under quota restrictions. It is also one of the considerations pointing to the belief that by concentrating water and other growth factors on the most responsive land, total production can be increased at lower operation costs.

4. As a basis for interpreting results of soil moisture analyses in the field, the moisture equivalent survey is indispensable. Previous discussion has demonstrated that a relatively small proportion of the total water in the soil after irrigation is actually available for plant growth. Unless an index, such as the moisture equivalent, of the soil's ability to hold and retain water is known, total moisture determinations are valueless.

Use of the Investigations on Plant and Water Relations:

One of the outstanding advantages of the general investigation in relation to commercial irrigation over the formal field experiment, in which results are not available

until the crop is harvested, is that we were able to apply some of the information acquired within six months of the start of the studies. The relationship between cane growth, soil type, and irrigation water was shown so clearly and indisputably by frequent measurements of the progress of the crop that the results could be applied immediately and without question to similar commercial areas. A general increase in plantation irrigation efficiency was reflected in faster applications of water during the summer growth months, more infrequent irrigations during the winter when soil moisture was high, and a better realization by all concerned of the value of water and of the causes and effects in commercial irrigation.

General interest in the results of the field investigations resulted in frequent requests from the plantation management and from division overseers for information on the soil moisture status of areas not included in the original studies. Such information was particularly valuable in deciding the date to resume irrigation after general rains, and in deciding the proper irrigation interval on various areas during hot summer weather. These requests were met by using the moisture equivalent survey as a basis for estimating the limits of soil moisture available for cane growth, and by obtaining total moisture samples from soil areas at or close to the moisture equivalent sampling site. By comparing the "relative wetness," or ratio of the two values, a serviceable guide to the amount of water already used between the date of last irrigation or rainfall and the date of sampling was obtained, as well as the probable number of days before the area would again need irrigation.

Index Stations for General Plantation Control:

A carefully planned program of soil moisture and cane growth measurements over the entire plantation was inaugurated in 1936 as a guide to better irrigation control and performance. In each field harvested during the 1936 crop, one or more stations were established on the basis of the moisture equivalent survey and inspection and consultation in the field with division overseers and water lunas. The number of stations in each field depends upon changes in soil type and field slopes within the area, but averages one station for every 50 acres under irrigation. At each field station, soil moisture determinations and cane growth measurements of 10 marked stalks are taken at weekly intervals. The results are reported to the head overseer, the irrigation overseer, and the division overseer concerned in terms of acre-inches of water still available in the soil, the rate at which moisture has been extracted from the soil during the period between the last irrigation and the current sampling, and the proper interval between irrigations under prevailing conditions if the soil moisture reservoir is to be filled before cane growth is checked because of inadequate soil moisture. The reports are used in supporting or modifying the scheduled irrigation interval on which water distribution is based, in indicating areas which require immediate or special attention, and in determining more precisely the date of starting irrigation after general rainfall. The data on weekly growth rates trace the development of the crop, indicate the relative response of various areas to fertilizer and water applications, and form a sound basis for crop estimates.

TYPICAL REPORT OF SOIL MOISTURE AND CANE GROWTH OBSERVATIONS
SOIL MOISTURE INDICATIONS

Division Ranch Date: Oct. 13, 1936

Field	Sta. No.	Field Capacity Ac.In./Ac.	Available Ac.In./Ac.	Extraction Rate Ac.In./Day	Days after Irrig.	Proper Interval (days)*	Cane Growth (feet) This Week	To Date
R—3	25	3.33	0.73	.29	9	11	.36	4.61
R—2B	27	3.40	1.82	.23	7	15	.25	14.10
R—2B	28	3.66	2.01	.28	6	13	.20	13.87
R—9	30	2.90	0.92	.17	12	17	.15	11.73
R—10A	33	3.33	0.43	.36	8	9	.30	8.52
R—10A	34	3.43	1.09	.20	12	17	.27	7.64
R—1	41	3.14	—0.56 (Subsoil dry)	.45	8	7	.17	2.12

* Days after last irrigation.

Cost of Irrigation Investigations and Control

The irrigation investigations at Waialua are designed to furnish a maximum amount of useful and applicable information with a small, well-organized staff. One clerk maintains the 64 water-measurement stations now in operation on the plantation, changes and reads the meter charts, and makes out all water reports. Another clerk posts all labor and field irrigation data, prepares interval and round reports, maintains the meteorological station and plantation rainfall reports, and is responsible for the preparation and filing of all other reports and memoranda. A laboratory clerk is responsible for the analyses of soil moisture and cane growth determinations, makes the reports on soil moisture indications, and prepares all charts, graphs and other drafting. A crew of three men in a light truck obtains the soil moisture samples and makes the cane growth measurements at about 40 field stations each day, covering the entire 10,000 acres of the plantation weekly.

Results of Irrigation Investigations and Control on the Plantation

The final analysis of the value of any operation lies in its ability to produce results and to reduce costs. Increased irrigation efficiency at Waialua over the past few years has been due to a number of related causes: favorable conditions of water supply and rainfall in 1935 and 1936, greater area planted and better physical condition of the fields, increased area under more efficient methods of irrigation, and a concerted and determined effort on the part of all concerned to obtain maximum results with labor and water. Perhaps the most gratifying result directly attributable to irrigation control has been the complete elimination of disputes over water distribution between divisions, the friendly competition in establishing new records of efficient irrigation, and the interest and concern of water lunas and field irrigators in the "acre-inches" in their areas. The soil moisture investigations have justified themselves in one season by providing a rational basis for shutting down high-cost pumps and reducing irrigation expense in areas of high soil moisture.

The consistent increase of irrigation efficiency at Waialua over the past three years is shown as follows:

ANNUAL IRRIGATION PERFORMANCE, WAIALUA AGRICULTURAL CO., LTD.

	1936	1935	1934
*Total Area Irrigated	155,036	126,773	143,666
Million Gallons Water Delivered	29,067	25,554	31,464
Acre-Inches per Acre per Round	6.90	7.42	8.06
Acres Irrigated per M.G. Water	5.33	4.96	4.57
Number of Man-days Irrigating	54,118	58,649	83,783
Acres Irrigated per Man-day	2.86	2.16	1.71
Per Cent Total Area in New Methods	36.8	22.9	9.5
Tons Cane per Acre	86.37	81.82	75.51
Tons Sugar per Acre	11.29	11.12	10.87

* Number of Acres under Irrigation × Number of Rounds of Irrigation.

The scientific tools of water measurement, soil moisture analyses, and crop measurement are being used successfully and practically on a representative sugar plantation. The application of scientific procedure to commercial irrigation has been a logical development of basic principles demonstrated under carefully controlled conditions, and a close scrutiny of these principles as applied to general field areas. Each step of the development has been made only after careful consideration, and only when the probable results could be seen in the light of direct application to more efficient irrigation and lower production costs.

Success in the use of scientific tools in irrigation is entirely dependent upon mature judgment in the application of the data, complete cooperation of the plantation executives, and a real interest on the part of the plantation field staff. Given such conditions, a similar program of irrigation control and investigation should prove an excellent investment for any plantation on which production costs are largely dependent upon economical field irrigation.

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The Value of Irrigation Water as a Factor in Interval Control

By H. A. Wadsworth

Recent studies upon the general relationships existing between soil moisture and cane growth (3) have developed a practical field technique for determining suitable irrigation intervals when the end in view is to secure maximum yields of cane at minimum costs. It is evident that the proposed procedure finds its most immediate application on plantations enjoying unlimited water resources at a fixed cost per unit volume of water. When such conditions exist it should be possible through the application of established principles, to reduce waste of both water and labor to an economic minimum.

Unfortunately such conditions do not often prevail on sugar plantations in Hawaii. Mountain streams are subjected to great fluctuations in flow. And too often such variations are synchronous with variation of rainfall in the cropped area. Thus full streams and consequently full ditches are available when the need for them is least. Conversely, limited water resources in gravity canals are usually associated with fields at or near the permanent wilting percentage and under such climatic conditions that the time between rounds should be markedly reduced. The so-called "Waialua Procedure" is unquestionably of great value under such conditions since it limits losses of water, but alone it provides no measure of the economic value of an irrigation upon fields of varying ages.

The general recognition of this problem is not new. For instance in 1928 Alexander (2) reported the results of three years intensive study at Ewa. Here the relative values of irrigation water applied to young ratoons, young cane, and cane in the "boom stage" were discussed and definite priorities established toward the end of the most economic use of available water resources. More recently Agee (1) has discussed the relative values of irrigation water on fields of different ages under conditions of extreme water shortage. But here emphasis is placed upon increasing amounts of water required per round in older cane rather than upon the sugar-producing ability of the water when applied to cane at different ages.

Cost and Value:

We are all apt to confuse the cost of water with its value or if this is not done, to assume that the value of water increases uniformly over a plantation as scarcity develops without distinction between fields in the different age groups. But it is evident that neither is correct. The cost of water is readily ascertained in any particular situation if all necessary data are available; the value of water is a complex function of many variables. To determine the momentary value of water week by week and field by field is a difficult and perhaps impossible task, but we can strive for an estimate of its value.

Although professional economists may object, it may be suggested that the *value* of irrigation water is measured by its ability to produce wealth or, in our case by

its ability to produce sugar. By this definition mountain water being allowed to waste at spillways or in leaking reservoirs has no value although it does have cost. Water lost into the subsoil by faulty or poorly supervised irrigation methods falls into the same category, but water applied to fields producing sugar at the rate of a ton or more per acre per month may have a value equal to many times its cost. One must be quick to remark that not all the water developed can be expected to bring in any such returns. Fields past the age so aptly called the "boom stage" by Alexander may well be kept growing but here the return of sugar per unit of water is lower, although to a certain point is still on the profit side. Moreover young fields must be kept coming against next year's grinding season. Here the value of the water lies in the protection of the investment made in that planting and not in the worth of immediately recoverable sugar. In the consideration of these values, and the determination of what sacrifices may best be made in time of severe water shortage, are problems that would challenge the skill of Agee's (1) plantation evaluator.

It is probable that immediate objection will be made to the implied statement that the worth of the sugar produced is to be credited to the irrigation water. Fertilizer, cultural practices, pest and disease control all contribute beyond doubt; adequate and timely irrigation would be futile without the high developments that have been secured in these fields. But for the sake of simplifying a complex situation it may be considered that on intensively irrigated plantations irrigation manipulation is the most potent single variable in the hands of the management.

The Problem of Water Evaluation:

Vague as the problems suggested above may be and poorly equipped as we may find ourselves to solve them in terms of dollars and cents, we may find some method of approximation which will at least give relative values. Apparently the plantation cost figures, which supposedly would be available, form the crux of the study. Our irrigation evaluator, to again use the borrowed phrase, would know the cost history of every field with its component items of general overhead, land preparation, cultivation costs and fertilizer as well as the cost of water and the labor used in applying that water. Against this accumulating cost is to be set the hope of sugar yield. From recent work at the Experiment Station we are led to believe that recoverable sugar is to be found in the cane at an age of six months, that the rate of sugar formation reaches a maximum of perhaps one ton per acre per month between the ages of nine months and twelve months after which the rate falls off rather rapidly. It is these rates that our irrigation evaluator must consider. He must balance the rate at which cost is increasing in any field with the rate at which recoverable sugar is being formed. He would suggest harvesting a field, if other things are equal and if irrigation water be abundant, when an additional unit of water does not give promise of value in excess of cost. In case of limited water resource he should be able to give the sugar producing value of water on every field and to recommend the harvesting of those fields upon which the value of water was lowest in terms of tons of sugar per acre-inch, or dollars worth of sugar per dollars worth of water.

A Hypothetical Case:

The illustration of a principle by an assumed case is unsatisfactory since the making of the assumptions themselves sets up a special case from which it is simple to reason that the general principle lacks local application. Such a case can be so simplified that it may be used as an example which may be elaborated as local conditions warrant. The figures chosen are entirely arbitrary, apply to no particular plantation, but may possibly be close enough to the truth in some to illustrate the scheme.

The first figure at the hand of our evaluator is the overhead which must be borne by each producing acre. For this figure we may, for illustrative purposes only, take $36 per acre per year or $3.00 per acre per month to cover the general sums of overhead plus the salaries which are directly chargeable to field operations. Moreover certain charges accumulate as soon as operations start on any particular acre. The cost of land preparation and planting may be spread over say four crops. When considered in this way the cost of land preparation may be added to the general overhead for that particular acre or field and used as an annual or monthly charge.

But here any possibility of charging each acre a given sum each month ceases. Young fields are being fertilized and cultivated while older ones are long since passed this stage. Moreover irrigation costs will vary not only from field to field but from month to month. Apparently our evaluator must keep a record of the cost of each field, month by month; but this figure is probably already available in the records of our hypothetical plantation. The assumed costs for these operations are indicated in Figs. 1 and 2.

In Figs. 1 and 2 we have two fields of plant cane, one started in April and one in September. Each acre of each field carries the general plantation overhead of $3.00 per acre per month as well as an additional charge of say $0.75 per acre per month to pay interest on the money spent in land preparation and to provide for the complete amortization of this charge in the expected life of the planting. Additional charges of fertilization, irrigation, and cultivation are also reported upon the basis of assumed costs.

In all cases these charges are reported as dollars per acre per month and are so plotted that the total cost of a field as of any date is measured by the area to the left of that date line and below the sequence of upper ordinates.

Harvesting and milling costs have purposely been omitted. Our irrigation evaluator is interested only in field costs and works under the assumption that his job is to put the greatest amount of sugar in the cane for the least cost. Consequently it is necessary to make one more assumption in order that we may establish a figure for the value of sugar in the cane in the field. For this figure, and with the usual reservations, we may use $30.00 per ton leaving perhaps an equal amount to cover the multitude of subsequent charges. One should say at once that an exact figure is not necessary since we are interested in relative values. Regardless of the specific value chosen the results would appear in the same relative position.

If, then, this assumption of a field value of $30.00 per ton for sugar in the cane is tenable we can superimpose curves upon our cost charts which will indicate the rate at which recoverable wealth is accumulating in the fields in question. Here, experimental evidence is only fragmentary but is well enough established for illus-

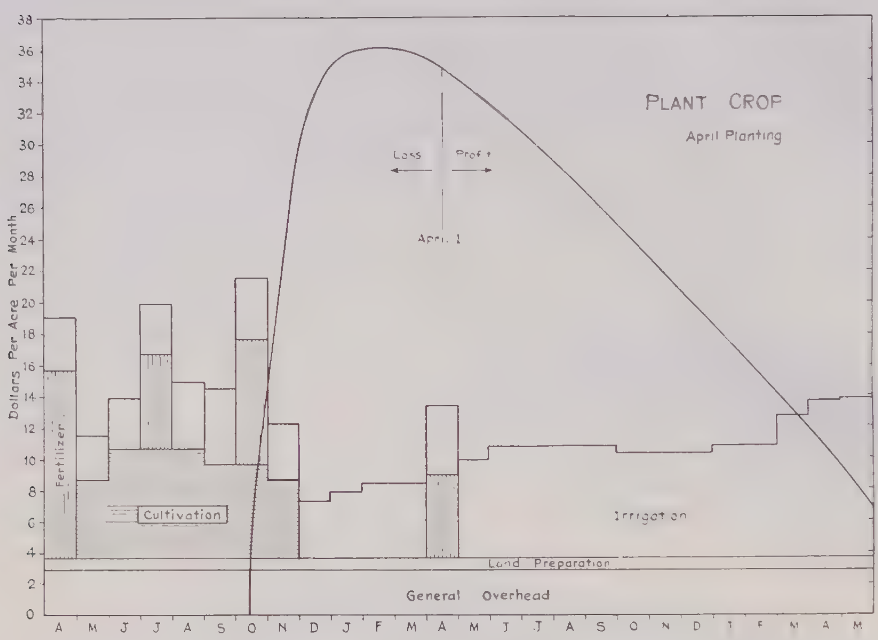

Fig. 1. Basic cost and sugar value chart suggested for determination of relative values of irrigation water. Here the crop is started in April, reaches its maximum rate of sugar production in the following February and begins to show profit on April 1. The assumed costs, upon which the figure is based, are entirely arbitrary and of value only for illustration.

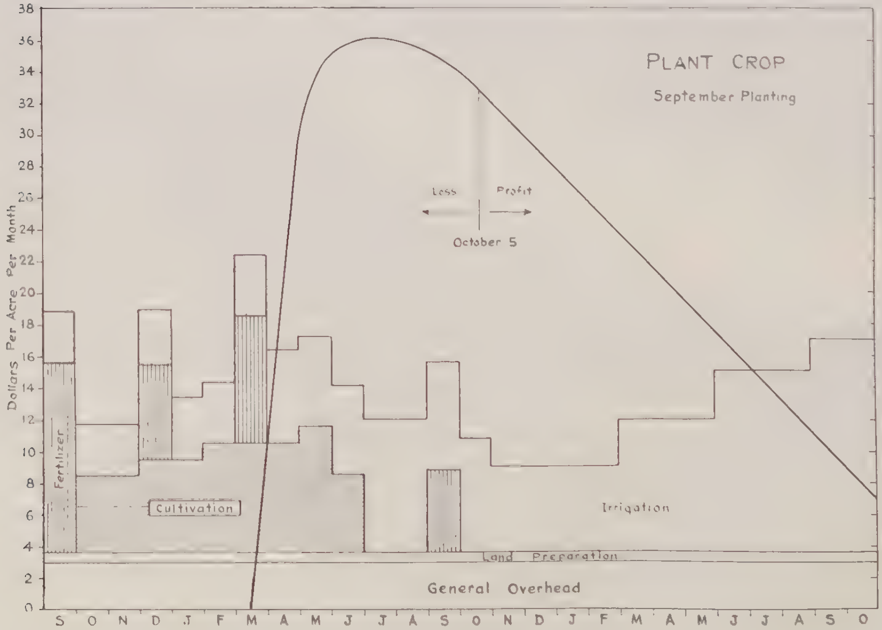

Fig. 2. The possible cost-value relationships for a crop started in September. Here, the time of maximum rate of sugar yield is given as June in place of February and loss turns to profit on October 5 in place of April 1. Again, the basic data are purely hypothetical.

trative purposes. The procedure by which they are secured is well enough fixed to permit our evaluator to keep track of the rate of sugar formation in the fields under his care with sufficient precision.

Again, the curves are plotted against time in months, the vertical ordinate being dollars worth of sugar per acre per month. And, again, the areas under the sugar curves represent the visible wealth in sugar.

Several conclusions can be reached from such curves. We might conclude, for instance, that somewhere between October and November with the April planting the rate at which recoverable sugar is formed is equal to the rate at which money is being spent on the field. Of much greater significance is the conclusion that on April 1 in the case of the April planting the estimate of recoverable sugar equals in value the investment to that date. The corresponding date for the September planting is October 5. Profit can come only when the area under the sugar curve equals the area under the cost curve.

Again, if water be taken as the major single item leading to growth we can estimate the *value* of water in terms of potential sugar production. For instance, in Fig. 1 we see that an application of about $5.00 worth of water in March of the second year has produced $36.00 worth of sugar; this ratio consistently decreases after that date.

The picture prior to the beginning of the formation of recoverable sugar is not so clear. We may assume that if the irrigations were not applied the total investment to date would be lost by the death of the cane, resulting in the necessity of starting over. But as everyone knows some cane varieties can exist for months without available soil moisture although they may make no growth. Or we may credit the irrigation water only with the overhead charges which it is protecting, assuming that the returns from charges for cultivation and fertilization are not lost, but simply postponed. Cost accountants will object to either of these alternatives, but to clarify the illustration let us use the second. During the early age the irrigation water is assumed to have a value equal only to the fixed overhead.

We can then prepare other curves from these data giving the *value* of water in terms of dollars worth of sugar per dollars worth of water for the two cases illustrated. Such curves are given in Fig. 3. It is evident that the value of irrigation water varies not only with the age of the planting but also with the time of the year at which the crop was started. During periods of abundant water supply this conception is of no great value; during periods of real or threatened scarcity it should furnish a valuable guide to the placing of irrigation water in order that the greatest profit may return from its use. For example, in July during the first year of the fall planting a dollars worth of water will produce about five dollars worth of sugar if applied to the September planting. If applied to the young cane its value is almost exactly equal to its cost. The picture changes as time passes. In April of the following year water on the April planting has twice the value of water on the September planting. Moreover, the April planting has just reached the profit-making stage and is making net profit at its greatest rate. In November the lines cross. Here presumably water had equal value on the two locations. Plantation experience will doubtlessly dictate which of the two fields should be favored.

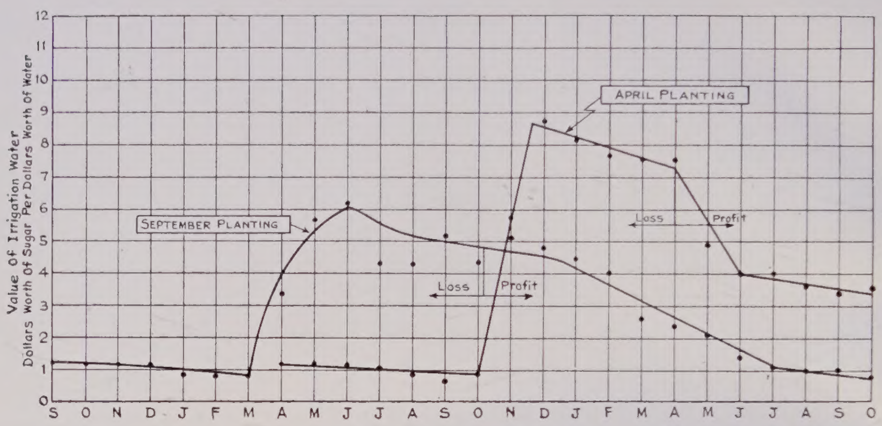

Fig. 3. A hypothetical expression of the *value* of irrigation water as a function of time of year and date of starting. Such curves, if they can be prepared, upon the basis of fact should form valuable guides for irrigation management in time of water shortage.

Discussion:

It is evident that the proposal to trace the value of irrigation water throughout the crop history is based upon assumptions which may not be sound enough to permit its use. This is particularly true with respect to the highly conventionalized curve which purports to represent the rate at which sugar is formed. New varieties, particularly those which may be cut annually, still further complicate the picture insofar as the time-sugar curve must be distorted for such varieties, although its real position is not known.

However, such difficulties do not materially reduce the desirability of such a procedure if the factual background can be improved. Field technique with respect to stalk counts, stalk weights, and the interpretation of juice-quality figures from random samples, has improved so markedly that it is highly probable that the "sugar-in-sight" curve can be built up as time passes without the necessity of making any assumption on this account. Moreover, when once established as a part of plantation routine no significant costs would be involved.

The value of such a procedure can only be determined by trial. It must be well recognized that many unforeseen difficulties would present themselves during such a trial; but with present facilities it is inconceivable that such difficulties would be insurmountable. If a simple but effective scheme for using water during a real or threatened drought can be devised the management would be equipped with still greater flexibility in the administration of one of its most valuable assets.

The correlation between such a scheme of using irrigation water on fields on the basis of positional value and the conventional determination of irrigation desirability by means of cane growth studies or soil moisture history is evident. In operation, concurrently, one might expect extreme economy in irrigation administration.

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Sugar Prices

96° CENTRIFUGALS FOR THE PERIOD
MARCH 15, 1937, TO JUNE 14, 1937

Date	Per Pound	Per Ton	Remarks
Mar. 15, 1937......	3.52¢	$70.40	Cubas, 3.50; Cubas, 3.54.
" 16...........	3.51	70.20	Cubas.
" 19...........	3.45	69.00	Puerto Ricos.
" 24...........	3.505	70.10	Puerto Ricos, 3.50; Cubas, 3.51.
" 25...........	3.54	70.80	Puerto Ricos, 3.53; 3.55.
" 29...........	3.555	71.10	Puerto Ricos, 3.55; Cubas, 3.56.
Apr. 1...........	3.50	70.00	Virgin Islands.
" 2...........	3.4275	68.55	Puerto Ricos, 3.45; Cubas, 3.47, 3.49; Philippines, 3.50.
" 3...........	3.45	69.00	Puerto Ricos.
" 5...........	3.455	69.10	Puerto Ricos, 3.45; Cubas, 3.46.
" 9...........	3.43	68.60	Philippines.
" 12...........	3.45	69.00	Puerto Ricos.
" 16...........	3.505	70.10	Puerto Ricos, 3.50; Cubas, 3.51.
" 19...........	3.505	70.10	Puerto Ricos, 3.50; Cubas, 3.51.
" 20...........	3.505	70.10	Puerto Ricos, 3.50; Cubas, 3.51.
" 22...........	3.47	69.40	Philippines.
" 24...........	3.45	69.00	Puerto Ricos.
" 26...........	3.48	69.60	Cubas.
" 27...........	3.46	69.20	Cubas.
" 28...........	3.455	69.10	Puerto Ricos, 3.45; Cubas, 3.46.
" 30...........	3.40	68.00	Philippines.
May 4...........	3.455	69.10	Puerto Ricos, 3.45; Philippines, 3.45; Cubas, 3.46.
" 6...........	3.45	69.00	Puerto Ricos.
" 14...........	3.39	67.80	Puerto Ricos, 3.38; Virgin Islands, 3.40.
" 15...........	3.38	67.60	Philippines.
" 18...........	3.35	67.00	Puerto Ricos.
June 10...........	3.395	67.90	Philippines, 3.38; Puerto Ricos, 3.40; Cubas, 3.405.
" 14...........	3.4025	68.05	Philippines, 3.40; Cubas, 3.405.